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THE OZARKIAN AND ITS SIGNIFICANCE IN THEORETICAL GEOLOGY.

I. THE OZARKIAN.

In 1886 I published a paper entitled "A Post-Tertiary Elevation of the Sierra Nevada, as shown by the River-beds."[1] Again in 1891 I published a paper on "The Mutual Relations of Land Elevation and Ice Accumulation during the Quaternary Period."[2] The following paper may be regarded as a continuation of the lines of thought suggested by the two preceding.

By continued reflection on the enormous changes that occurred in the western part of the continent at the end of the Tertiary, I have been led to recognize the existence of an epoch of long duration and of great importance immediately preceding the time of the invasion of the ice sheet. On account of its great importance this epoch certainly deserves a distinctive name. For want of a better, I adopt that of the "Ozarkian," given it by Hershey.

History of the name.—The epoch was first recognized by Hilgard and more distinctly by McGee, as the post-Lafayette uplift,

[1] Am. Jour. Sci., Vol. XXXII, p. 167, 1886.

[2] Bull. Geol. Soc. Am. Vol. II, p. 329.

shown by extensive erosion of the Lafayette gravels all over the southern states. But a distinctive name was first given it by Hershey,[1] who called it Ozarkian in commemoration of its work in the formation of the remarkable gorges of the region of the Ozark Mountains. He, however, fully recognized its importance as a time of general uplift and erosion, but regarded it as only an episode comparable with the Kansan or Iowan episodes of the Glacial epoch. The name was adopted, though somewhat reluctantly, by McGee (Sci. III, 796, 1896), and its importance more fully recognized,[2] but he regards it as belonging to the Pliocene and not the Quaternary. This point we shall discuss later. A little later (Am. Geol. XVII, 389, 1896) Upham also adopts the name, and, like Hershey, refers it to the early Quaternary, but advances it to a *primary* division of that period comparable with the Glacial. But even yet, it seems to me, its full importance is scarcely recognized unless it be by McGee, and its true significance entirely overlooked. Indeed both its importance and its significance are brought out in strong relief only by the study of its phenomena in the western part of the continent and especially in California.

If with Upham we divide the Quaternary period into three epochs, the Ozarkian, the Glacial, and the Champlain, then the Ozarkian was by far the longest, in fact, longer than both the others put together. Or again, if the Quaternary be divided into two epochs, the Ozarkian and the Glacial, the Champlain being merged into the Glacial, as is commonly done by European geologists, then of the two, the Ozarkian is by far — perhaps by many times — the longer. In many ways the Ozarkian is strongly contrasted with the other epochs of the Quaternary. If, for example, we adopt the division into three epochs, these are characterized each in its peculiar way; the first, by elevation; the second, by ice accumulation; the third, by depression; the first, by immense erosion; the second, by glaciation and drift deposit; the third, by stratified deposits in seas and lakes.

[1] Science III, 620, 1896.

[2] "The reference of the Ozarkian to the Pleistocene would multiply by many times the commonly recognized duration of that period." McGee, Sci. III, 796, 1896.

The Ozarkian has heretofore attracted little attention, because until very recently geological history was supposed to be recorded only in stratified rocks and their contained fossils; but this being a period of continental elevation and enlargement, it has left no strata exposed to view. Geological history was at that time recorded only by erosive work. So far as stratified rocks and fossils are concerned, this is a period of lost record—it is a *lost interval*.

I said that the real importance and significance of this epoch is best seen on the western part of the continent. I must justify this assertion by a comparison of the phenomena in different parts of the continent.

1. *The eastern part.*—In the eastern part of the continent, the work of erosion of this time is seen in the so-called old river-beds deeply underlying the present beds and extending beyond their limits on each side, and especially continuing beyond the limits of the present continent, as submerged channels trenching the submerged continental shelf, notching deeply its margin and opening out into the abyssal waters of the true oceanic basin. It is shown also not only in the deep gorges of the Ozark region, not only in the deep and widespread erosion of the Lafayette gravels in the south, but also in the highly emphasized topography underlying the drift all over the glaciated region of the north. By means of the submerged channels the amount of vertical elevation of the eastern portion of the continent has been estimated as certainly not less than 3000–5000 feet and may have been much greater. Similar evidences of elevation are found on the Pacific coast and also on the coasts of Europe and of Africa. We have every reason to believe that it was a time of almost universal continental elevation and enlargement.

Heretofore these old rivers of the east have been referred, like those of the west, to the Tertiary times and called Tertiary river-beds; although it is admitted that they were occupied and deepened by the ice of the Glacial times. The Tertiary erosion was supposed to have graded insensibly and continuously into that of the Glacial, but the greater part was attributed to the

Tertiary; and the post-Tertiary erosion was supposed to be wholly Glacial. According to my view, on the contrary, the post-Tertiary erosion was by far the greater and was pre-Glacial in time, *i. e.*, Ozarkian.

In the eastern portion of the continent, therefore, the Ozarkian grades into the Tertiary, but is well marked off from the present by the depression and sedimentation of the Champlain.

2. *The mid-continental or plateau region.*—In the plateau region, on the contrary, the Ozarkian work is sharply marked off from the Tertiary, but grades insensibly into that of the present.

It is well known that the plateau region has been rising ever since the end of the Cretaceous—that from being the lowest part of the interior continental basin, it has become the highest part of the continental arch. The amount of elevation during this time has been at least 20,000 feet, about 12,000 of which has been carried away by erosion, leaving still 8000 feet of general elevation. Of this enormous general erosion, the largest part—shown by the receded and still receding cliffs—probably belongs to the Miocene. The canyon-cutting is certainly post-Miocene. The outer canyon (of the Grand Canyon) ten to fifteen miles wide and 3000 feet deep, belongs to the Pliocene; while the inner gorge, 3000 feet deep but very narrow, belongs to the post-Pliocene, *i. e.*, to the Ozarkian and the present.

I said the Tertiary work is sharply marked off from the Ozarkian but the Ozarkian grades insensibly into present. The evidence of this is given by Dutton, as follows:

Between the Pliocene work of the formation of the outer canyon, and the subsequent work—Ozarkian to present—the cutting of the inner gorge, there was an interval of rest marked by a wide shelf between the two. The rising and the down-cutting was continuous during the Pliocene until finally the river reached its base level of erosion and rested from further downward cutting and commenced to sweep from side to side widening its channel, until the canyon walls were nearly ten miles apart. Then began the Ozarkian rise and the beginning of the

cutting of the inner gorge, which has continued to the present time. The elevation during the Tertiary was regional, the elevation which commenced with the Ozarkian was continental or even more widespread. In the east there was a sharp demarcation of the Ozarkian from the present erosion by the Champlain depression and sedimentation; which depression, as I suppose, was determined by the weight of the ice sheet. But in the plateau region there was no ice sheet — it did not extend so far — and therefore there was no depression and therefore no interruption of the erosion to the present time; for the rising is still progressing. The whole series of phenomena in this region may be well explained by a local rise continuous from the end of the Cretaceous till now, except that it was interrupted at the end of the Pliocene by the Lafayette depression of McGee and afterwards greatly enhanced by the general continental elevation of the Ozarkian.

3. *Sierra region.* — But it is in the Sierra region alone that we find the Ozarkian erosion-work sharply marked off both from the Tertiary on the one hand and from the present on the other. It is here therefore that the distinctive Ozarkian work can be best studied.[1]

Brief history of the Sierra.—The Sierra Nevada, as is well known, was formed at the end of the Jurassic by lateral pressure and strata-folding in the usual way. What kind of a mountain it was at that time, how high, and what its configuration we know not; for the continuous erosion of the Cretaceous and Tertiary times had nearly swept it clean away. The cycle of its mountain life had reached its last stages. By continuous erosion it had been reduced to a peneplain, with its wide-sweeping curves of broad shallow channels and low-rounded divides. The rivers had reached their base levels and rested. This was the work of the Cretaceous and Tertiary.

Then came the post-Tertiary rejuvenation of the mountain

[1] As the term *Ozarkian* had already been used by Broadhead for a Lower Silurian series in the Ozark region (Am. Geol., XI, p. 260, 1893) there may be an admissibility of its use in this connection. If so, I would propose the name *Sierran* as far more appropriate.

life,[1] by the formation of a fissure on the eastern slope, the heaving of the whole mountain block on its eastern side with a great eastern fault-scarp,; the transference of the crest to the extreme margin with great increase of the western slope and consequent revival of the erosive energy of the rivers. Coincident with this in middle California there was a great outpouring of lava which ran in streams down the western slope, filling up the old river beds, and displacing the rivers. The displaced rivers, with recently and fiercely aroused energy, immediately commenced cutting new channels, which are now 3000 to 6000 feet deep, and far below the old; so that these latter are left with their lava-covered gravels high up on the present divides This was the work of the Ozarkian. This intensely interesting geological story has been so often told that we only recall here its outlines in order to apply them to the case in hand.

In southern California, beyond the limits of the lava flows this post-Tertiary elevation and revival of erosive energy was fully as great, or even greater than in middle California; but the rivers were not displaced, and therefore they continued to cut in the same places, but to far deeper levels; so that the margins of the wide old river beds with their gravels are left hung up high on the sides of the present canyons.[2] The distinction, however, between the wide shallow tertiary troughs and the deep narrow post-Tertiary canyons is equally sharp here.

We have spoken thus far only of the deep canyons which trench the western slope as being of post-Tertiary origin; but the same is true also of the whole scenery of the high Sierra. It all belongs to the post-Tertiary, and its bold, rugged, savage grandeur is due to its extreme recency. The wildness of youth has not been yet tempered and mellowed by age.

It is evident then that the Ozarkian is here sharply marked off from the Tertiary. How is it in regard to its relation to the present? In the lower parts of the canyons the Ozarkian grades insensibly into the present, for the rivers are still cutting. But

[1] Am. Jour. Sci., Vol. XXXII, 167, 1886.

[2] Am. Jour. Sci., Vol. XXXII, 174, 1886.

in their upper parts the two are separated by the glacier erosion. The upper canyons were occupied by glaciers, and the comparison of these upper with the lower canyons shows that while their forms were modified, and perhaps their depths somewhat increased, they were not made by this agency. This was mainly the work of the post-Tertiary but pre-Glacial times, *i.e.*, of the Ozarkian. But the glaciation serves to show how much has been done by water since the Glacial, *i. e.*, during the present times; and we find it very insignificant.

In conclusion, no one who sees and reflects upon the prodigious work done in the Sierra since Tertiary times can resist the conviction that even making all due allowance for exceptional energy and rapid work, determined by high slope and also for other causes of rapid work explained in a previous paper,[1] the time necessary must have been enormous — many times as great as any reasonable estimate of the duration of the Glacial epoch.

II. SOME MODIFICATIONS OF MY PREVIOUS VIEWS.

In the article already alluded to, on the "Relation of Land Elevation and Ice Accumulation" I attempted to reconcile the two antagonistic views in regard to the attitude of land during the Glacial epoch. According to some writers the land in high latitude regions was greatly *elevated;* according to others it was on the contrary *depressed.* According to the one, the intense cold and ice accumulation was the direct result of the elevation, and a subsequent depression produced a moderation of the climate and a melting and final disappearance of the ice; according to the other, the ice accumulation was not coincident with the elevation and, therefore, there must have been some other cause for the cold and ice accumulation. In the paper referred to I showed that all the phenomena might be satisfactorily explained by supposing that the elevation was the cause of the cold — the cold the cause of the ice accumulation — the weight of the accumulated ice the cause of the depression — the depression the cause of returning

[1] Origin of Transverse Mountain Valleys, Univ. Chronicle, Vol. I, No. 6, p. 179, 1898.

warmth — the warmth the cause of the melting and retreat of the ice, and finally that the removal of the ice-load was the cause of the re-elevation to the present condition; but — and this is the distinctive feature of my view — that in all these cases *the effects lagged behind the causes.* I showed that this was so in all cases of accumulated effects, but would especially be true in this case. To illustrate these relations I used a diagram which I here pro-

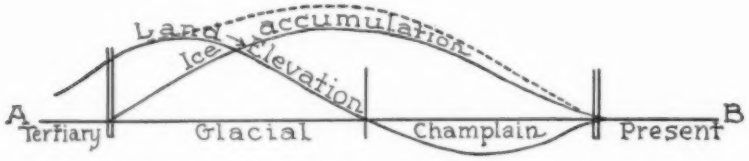


FIG. 1.— Diagram showing the relations of land elevation and ice accumulation during the Quaternary. *AB* — course of time and also the present status of earth crust. The dotted line shows elevation if it had not been interfered with by the ice-load.

duce. The legend will sufficiently explain it. By this view the Quaternary consists of two epochs, the Glacial and the Champlain, of nearly equal lengths. The one characterized by elevation and cold, the other by depression and warmth, but the extreme of ice accumulation lagged behind the extreme of elevation as seen in the figure.

I am more and more convinced that the principle of lagging is a true one and even more important than I at that time supposed. I now believe that I did not at that time make the lagging, especially in the matter of the accumulation of the ice-load, great enough. We must make a distinction in this regard between the intensity of the cold and the thickness of the accumulated ice. The cold probably responded somewhat promptly to the land elevation, but not so the ice accumulation. This was a very slow process and might lag to any degree behind the elevation and the cold. This we now proceed to show.

1. Snowfall depends on cold, but still more upon moisture.

Now there is nothing in the way of supposing — but on the contrary much reason to believe — that the period of great elevation was one of comparative dryness and that the climate became moister in the latter part when the elevation was not so great. This would make the ice accumulation lag behind the elevation and the cold.

2. But again: We must, of course, make a wide distinction between the annual snowfall and the rate of accumulation; for this latter is the result only of the annual *excess* of snowfall over waste by melting and evaporation, and this excess may be to any degree small.

3. As it is, the *thickness* and therefore the *weight* of the snow that we are here concerned with, it must be remembered again that there is still another and much more important source of waste antagonizing local accumulation and therefore increase of thickness, viz., the run-off — not the run-off as water but as ice by glacial motion. After a certain thickness is attained this run-off completely balances the annual excess over waste by evaporation and melting, and prevents, farther increase of thickness. This is the case now in all glacial regions. In the Alps, the Himalayas, etc., there is no indefinite increase of thickness because the run-off by glacial motion completely balances the annual excess. Similarly in Greenland, and the Antarctic continent although there is great excess of snowfall over waste by evaporation and melting, yet there is no increase in the thickness of the ice sheet because the excess is balanced by the run-off of the ice into the sea and the formation there of icebergs which are carried away by oceanic currents.

So also in Glacial times, after a certain thickness of snow had accumulated on any given area — say the Canadian highlands — the farther increase would be prevented, because balanced by the ice-sheet motion in all directions. Any increase of thickness would require not only excess but *increase of excess* and would be extremely slow because always kept in check by the increased run-off.

To sum up: Suppose, then, the highlands about Hudson

Bay to have been the center of elevation, of ice accumulation and of radiating run-off: Suppose farther, that the elevation commenced about the end of the Pliocene and was the cause of the cold. Then considering the previous warmth of the Tertiary times, it is probable that the elevation would go on for a long time and reach a considerable degree before there would be any snowfall at all in this region, and still much longer time before there would be annual excess over waste by evaporation and melting, *i. e.*, before there would be *perpetual snow.* After perpetual snow was reached, under the effect of the ice-sheet motion tending ever to bring about equilibrium, the increase of the thickness of the ice sheet must have been extremely slow. In fact, it is evident that no such thickness as actually occurred could

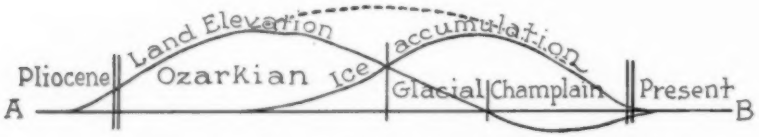


FIG. 2.—Diagram showing supposed relation of land elevation to ice accumulation, as now revised.

have been attained at all, but for the subsidence of the earth-crust under the weight of the ice. The increased thickness was conditioned upon and waited on the subsidence. I believe, therefore, that an increase of one inch per annum would be an extravagant estimate. At this rate it would take 150,000 years to make a thickness of 12,000 feet, which is the estimate of Dana. To this must be added the much greater time before the perpetual snow was formed at all.

Under the light of these estimates and especially of these new views of a long Ozarkian epoch preceding the glacial epoch, I would therefore modify my previous diagram, making the beginning of the ice accumulation much later and making both the Glacial and the Champlain much shorter than before, as shown in the revised diagram, Fig. 2. The greater distinctness of the Ozarkian from the Glacial is shown

III. SIGNIFICANCE OF THE OZARKIAN.

In my papers on *Critical Periods in the History of the Earth*, in 1877 and in 1898[1] I try to show that there are periods of great and widespread changes in the earth's crust, in climate, and in organic forms. These I call "critical periods" and insist that they separate the primary divisions of geological, time, viz., the *eras*. Being periods of great elevation and enlargement of continents, they are to a great extent "lost intervals," *i. e.*, periods in which the usual record of stratified rocks and contained fossils is interrupted. The last of these was the Quaternary. The Ozarkian was largely a lost interval so far as stratified record is concerned.

Great cycles in the evolution of the earth.—Now an era, *i. e.*, the time from one critical period to another, must be regarded as one great cycle of widespread changes; during which, however, there may have been and indeed undoubtedly were, subordinate and more local cycles. Such a great cycle was the Paleozoic, very regular in its course in this country. Such another great cycle was the Mesozoic, but affected in this country with a well marked subordinate division at the end of the Jurassic. Still another such great cycle and again very regular in this country was the Cenozoic, and such another, I am convinced, is even now commencing. I have called it the Psychozoic.

I have supposed these to be cycles in the evolution of the earth. They are, therefore, such in every department alike. They are cycles in the evolution of earth-forms, *constructively*, *i. e.*, by *interior* forces in continental elevation and mountain formation. They are cycles in the evolution of earth-forms, *destructively*, *i. e.*, by *exterior* forces and erosive sculpturing. They are cycles of evolution in climatic conditions. And, finally, as the result of all these, they are also cycles in the evolution of organic forms and their geographical distribution. Most of these various forms of cyclical movement I have discussed in my previous papers, especially that in 1895. These, therefore, I merely

[1] Am. Jour., Vol. XIV, 99, 1877. Bull. Geol. Dept. Univ. Cal., Vol. I, 314, 1895.

mention and pass on. Some, however, I discuss fully now for the first time.

1. *Cycles of constructive forms.*—Of the four great kinds of earth movements treated of in my address as President of Geological Society of America, December 1896,[1] the greatest, viz., that by which are formed oceanic basins and continental arches, being determined by unequal radial contraction in the secular cooling of the earth, which in its turn is the result of an original heterogeneity in the density and especially in the conductivity of different parts of the earth, must have a cycle coëxtensive with the life of the earth itself, and therefore may be left out in this discussion. But superimposed on this greatest, there are other cycles of oscillations of the earth's crust over wide areas—of continental elevation and depression, accompanied with the formation of great mountain ranges. These are the cycles of next importance, and with which we are here concerned; for they determine all other cycles mentioned above, and therefore the occurrence of what I call critical periods. They are demonstrated by the widespread unconformities which occur at these times. Upon these, again, are superimposed still lesser cycles which, however, do not concern us here. I have sufficiently treated of these, both great and small, elsewhere, and therefore pass on.

2. *Cycles of climatic conditions.*—Coincidentally with the changes by continental elevation and depression with their attendant mountain-making, there have undoubtedly been concurrent changes in climatic conditions of many kinds, especially of temperature. These changes were, on the whole, probably gradual throughout the era, but culminate and oscillate in the critical period which closed it and constituted one of its most marked features. The two most conspicuous examples are those which occurred at the end of the Paleozoic and at the end of the Tertiary. The early Paleozoic was eminently an oceanic period. During the whole Paleozoic there was, in this country at least, a gradual elevation and enlargement of the continent,

[1] Bull. Geol. Soc. Am., Vol. VIII, p. 113, 1897.; Sci., Vol. V, p. 321, 1896.

slow at first, but rapidly increasing toward the end and culminating in the formation of the Appalachian chain. Concurrently with this there was, almost certainly, a gradual decrease of temperature rapidly culminating at the end in something approaching, at least, a true glacial epoch in the Permian. Similarly, there was probably, during the Tertiary, a gradual elevation and increase of land and diminution of temperature, culminating somewhat rapidly at its end, in the Ozarkian elevation and the Glacial ice sheet. Similar changes occurred at other critical periods, but less conspicuously.

I have been accustomed, in default of any other and more probable cause, to attribute the increase of cold directly to the increase of elevation, although admitting its possible insufficiency. It is this apparent insufficiency that constitutes the only justification of extra-terrestrial theories of Glacial climate, such as Croll's, etc. Recently Professor Chamberlin has contributed to the JOURNAL OF GEOLOGY[1] some admirable and suggestive speculations on the cause of these cycles of climate and of life. According to him, the continental elevation is not the direct, but mainly the *indirect* cause of cold, by the exhaustion of the supply of CO_2 in the air by continuous rock-decay during these land-periods. This supply is supposed to be restored from the interior of the earth through fissures, etc., produced by the commotions of these times. He, moreover, correlates these changes in elevation and in temperature in a most suggestive way with alternating richness and poverty of life and corresponding alternations of limestones and sandstones. I cannot, of course, dwell on these very suggestive views, but only draw attention to the fact that the cycles of which Professor Chamberlin speaks correspond to the *smaller* or subordinate cycles spoken of on pages 536 and 537, and *not* to the great cycles separated by critical periods and constituting eras. Nevertheless, there is no reason why similar causes acting with greater intensity at long intervals should not determine the greater cycles also.

3. *Cycles of geographic diversity of organic forms and of rates of*

[1] JOUR. GEOL., Vol. VI, pp. 597, 609, 1898.

evolution.— We have already explained in a previous paper[1] how, during the course of a cycle, the geographical diversity of organic forms in isolated regions becomes greater and greater indefinitely as long as isolation continues, until finally synchronic correlation of strata in different regions becomes difficult or impossible. But that during critical periods (and to less degree at other times) there occur wide migrations and mingling of faunas and corresponding obliteration of geographical diversity, only to commence again with new isolations and a new geographical diversity increasing again with time. Thus there are alternations of increase and obliteration of faunal diversity. This idea has an important bearing on the doctrines of synchrony and homotaxy. At the beginning of a great cycle immediately after a critical period, geographical faunas commence, as it were, all abreast; synchrony and homotaxy are now in harmony. As time goes on, the newly mingled but re-isolated faunas develop in different directions and at different rates, become more and more divergent in character, and more and more different in grade of evolution. Synchrony and homotaxy become more and more discordant, until at the end of the cycle it becomes extremely difficult or even impossible to correlate strata of different countries synchronically. Then there comes another critical period of widespread oscillations of crust and readjustment to new conditions of equilibrium with accompanying oscillations of temperature and wide migrations of species and mingling of faunas and floras, hastening the steps of evolution everywhere, but obliterating geographical diversity, and, as it were, evening up again synchrony and homotaxy, only to commence a new cycle by re-isolation.

An attempt is made to roughly represent this process by a diagram (Fig. 3). In this diagram two cycles are represented. In the first, Europe is ahead, and increasingly so as the cycle goes on, and Australia is most lagging. In the second, North America is ahead. In each the divergence between synchrony (the full waving lines) and homotaxy (the horizontal dotted

[1] Bull. Geol. Dept. of Univ. of Cal., Vol. I, p. 314, 1895.

lines) becomes greater and greater until the end of the cycle, when there comes a critical period of wide migrations of species (represented by the horizontal arrows), a mingling of faunas, a fiercer struggle for life, together with the more active operation of other factors of evolution, and a consequent hastening of the steps of evolution everywhere, but especially in the lagging areas, to a more or less even general line. In the second cycle

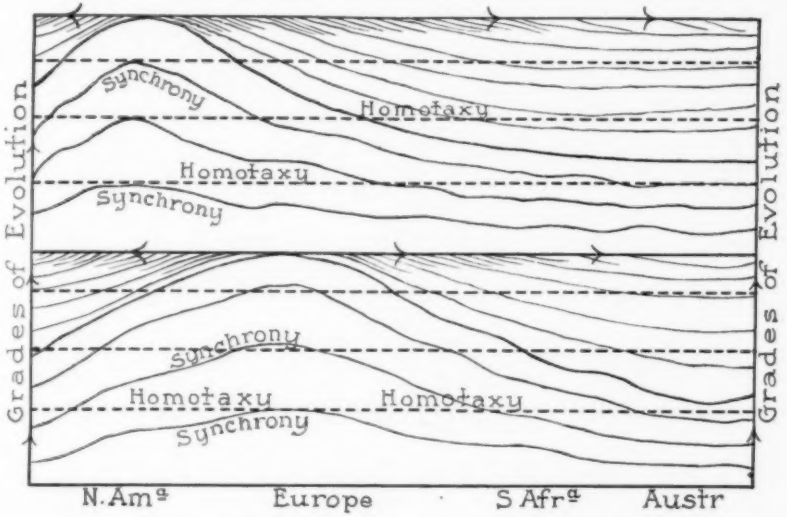


FIG. 3. Diagram showing the general relations of synchrony to homotaxy in geological times. Full lines represent the same time in different places (synchrony). Horizontal dotted lines represent equal stages in evolution (homotaxy).

the same process begins and progresses, except that now America is ahead, and increasingly so until the next crisis; when the synchronic lines are again evened up to parallelism with the homotaxic. If it were not for these occasional evening-ups a general geological history based on organic remains would be impossible.

The whole process may be likened to a long army line marching abreast over a broken country, led by officers, who may be compared to the dominant types. Soon the line

becomes irregular, and more and more so, until it is no longer discernible and all seems confusion. At certain intervals the leaders run along the lines hastening up the laggards until the line is re-formed. But the re-formed line again soon becomes irregular and falls into confusion, and is again re-formed, and so on.

Of course partial and more or less local readjustments of synchrony and homotaxy take place at intermediate times at the end of subordinate cycles. Sometimes in the general readjustment some locality may be left out. This is the case with Australia today. The last wide migrations and minglings of faunas and obliteration of geographical diversity, viz., that during the Quaternary, did not reach Australia, and therefore its fauna is still far behind in the race of evolution.

4. *Cycle of topographic forms by erosion.*— But there is still another cycle, and one with which we are especially concerned here, viz., the *cycle of erosion forms*. Every critical period is a time of the formation of great mountain ranges, and the crisis is usually named after the mountain range which forms its most conspicuous monument. Thus we have the Appalachian revolution, closing the Paleozoic; the Cordilleran, closing the Mesozoic. The pre-Cambrian crisis might well be called the Laurentian, and the one we are now specially dealing with, viz., the Quaternary or Ozarkian, might well be called the Basin Ranges revolution; for not only the basin ranges, but also the Sierra Nevada, the Coast Ranges of California, and the Mt. St. Elias Range of Alaska were either formed or else rejuvenated at that time.

Thus with every critical period there are new mountains formed and old ones rejuvenated; new lands formed by emergence of sea bottoms and old ones elevated or depressed. Thus new constructional forms are made and a new cycle of destructional or erosive forms inaugurated. These forms pass gradually through the stages so graphically described by Professor W. M. Davis and others, the final result being the so-called *peneplain*. Of course, there are subordinate, intermediate, and more local cycles; and therefore at the end of the great cycle

we may have examples of both old and new topography. But in any case a critical period, being the beginning of a new great cycle, after such a period we have only or mainly new topography. This is the true and conclusive answer to Professor Tarr's objection to Professor Davis' far-reaching deductions from the supposed discovery of the remnants of former peneplains. Professor Tarr objects that if there be any such former peneplains there ought to be peneplains formed now and in the present geological epoch—that the very foundation of geology as an inductive science consists in the use of causes and processes now in operation as the basis of reasoning on phenomena of earlier times. Yes, *causes* and *processes* now in operation, but not *results* and *forms* now existent and produced in the present epoch. Causes and processes are constant, or nearly so, but resulting forms pass through a regular cycle of evolution-changes. Now the *last cycle is just commenced.* We must wait at least a few millions of years before we can expect to find peneplains made out of the recently inaugurated and highly emphasized topographic forms. As a note of warning against hasty generalizations Professor Tarr's paper cannot be too highly commended. We are all too apt to be carried away by a new idea. It is apt to become a fashion of thought for which we are ever seeking confirmation; and in all complex and imperfectly understood questions, what we seek earnestly for we are very apt to find. It is possible, yea, it is probable, that the peneplain idea has been overworked; that many of these ancient peneplains exist only in the fervid imagination of the too ardent geologist. Nevertheless, the principle is a true one and undoubtedly a very fertile one. Geological history has heretofore been based almost wholly on the results of sedimentation. It is time that it should be based also, and equally, on the results of erosion. These results may be more difficult of interpretation, but difficulties ought only to stimulate investigation.

Is the Ozarkian Tertiary or Quaternary? Finally, we are now prepared to return to the question of place of Ozarkian in the geological classification. After what has been said the answer

to this question is plain. Critical periods, as I have shown in previous papers, are the great landmarks separating the primary divisions of geological time—the eras. They are the comparatively fixed points between which we correlate periods as best we can by comparison. Now, if the Quaternary be indeed one of these and the last, then it is evident that the Ozarkian, being a time of great elevation and enlargement of continents, and therefore a period of lost record, belongs par excellence to that period. It is the most important and characteristic part, and the part which determined the whole succession of changes which inaugurated a new order of things, viz., Present; a new era, viz., the Psychozoic. The Tertiary was a period of comparative quiet, of gradual changes, and abundant life. The Ozarkian commenced the series of evolutionary changes which inaugurated a new era and is the most characteristic and important epoch in the series.

That the Ozarkian belongs to the Quaternary, therefore, is certain. But the question still remains: to what era should we attach the Quaternary? Upham thinks that to be consistent I ought to put it in the Psychozoic, because *man* was introduced in the Quaternary.[1] On the contrary, I believe it should be allied with the Cenozoic. The Permian, too, is a transition. revolutionary, critical period between the Paleozoic and Mesozoic, But after much discussion it has been put with the Paleozoic. The Laramie is the transition, revolutionary, critical period between the Mesozoic and Cenozoic. Again, after long discussion, it has been put in the Mesozoic. So, also, the Quaternary is the transitional, revolutionary, critical period between the Cenozoic and Psychozoic. After some discussion it will undoubtedly be put in the Cenozoic with the Tertiary. It is true that man, the characteristic dominant type of the Psychozoic, was introduced in the Quaternary. But here, also, the analogy with other critical periods holds good. A new era begins when the readjustment and the new order is established. Reptiles were introduced in the Permian, but the reign of reptiles did not

[1] Am. Nat., Vol. XXVIII, p. 980, 1894.

begin until the Trias. Mammals were introduced in the Mesozoic, and even true mammals—eutheres—probably in the Laramie, but the reign of mammals did not begin until the Tertiary. So, also, man was introduced in the Quaternary and possibly even in the Pliocene, but for a long time he struggled doubtfully for mastery with the great beasts of that time. His supremacy was not established until after the Glacial epoch, *i. e.*, with the Psychozoic.

All I insist on, however, is that the Quaternary, wherever it is put, must all go together. It must not be split and its most characteristic part separated and put in the Tertiary. There may be, indeed, some good reasons for putting it *all* in the Tertiary, and analogy will bear this out. For example, it is customary to make three periods in the Carboniferous, viz., the Mississipian, the Coal Measures, and the Permian, but there is a growing tendency to unite the Permian with the Coal Measures as its uppermost transitional stage. Again, we may divide the Mesozoic into Triassic, Jura, Cretaceous, and Laramie, but it is more usual and probably best to unite the Laramie with the Cretaceous as its uppermost transitional stage. So, also, it is customary to divide the Cenozoic into two periods, Tertiary and Quaternary, but it may possibly be better to regard the Quaternary as the final transitional stage of the Tertiary, and thus to divide the Tertiary into four epochs, the Eocene, Miocene, Pliocene, and Pleistocene. All I insist on is that its most characteristic part and that which determined the whole series of changes characteristic of this time should not be separated from the rest.

A PLEA FOR PSYCHOZOIC AS AN ERA.

I again take occasion to insist on the present, as the beginning of a new era—the Psychozoic—separated from the Cenozoic by the last great critical period, the Quaternary. This must be so if the Quaternary be indeed a critical period comparable with those that separated the previous eras. That it is such is shown by the fact that it has all the characteristics of such periods. It is characterized (1) by widespread oscillations of

the earth's crust; (2) by the formation or rejuvenation of great mountain ranges; (3) by the formation of new constructional forms, and the inauguration of a new cycle of erosion forms; (4) by great climatic oscillations; (5) by wide migrations and minglings of faunas and floras, and fiercer struggle for life, and rapid changes of organic forms by wholesale destruction of old forms and evolution of new forms; (6) by more rapid steps of evolution, but a partial obliteration of previous geographic diversity, and the inauguration of a new cycle of increasing diversity; and (7) by the introduction of a new dominant type —man, who is now becoming more and more the great agent of change in the new era, especially in organic forms.

There can be no doubt that we are now in the midst of a change more sweeping and rapid than has ever before taken place in the history of the earth, but which we imperfectly appreciate because we are in the midst of it, and therefore lose the perspective. Why then should we hesitate to recognize that the present is indeed one of the prime divisions of geological time? It is more: it is that which alone gives significance to all that precedes.

JOSEPH LE CONTE.

AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS[1]

THERE are hypotheses and working hypotheses. The suggestion that the last glacial period was caused by the passage of the solar system through a cold region of space may be styled a hypothesis, but scarcely a working hypothesis in the geological sense, for it does not form the groundwork or incentive of geological inquiry. An astronomer might be moved to hunt for the cold spot, but it has no inspiration for the geologist. General suggestions of a possible cause do not reach the dignity of working hypotheses until they are given concrete form, are fitted in detail to the specific phenomena, and are made the agents of calling into play effective lines of research. The construction of a concrete working hypothesis suited to stimulate and guide investigation in a wholesome manner, and to take its place in competition with other hypotheses of like working potentialities, thereby inducing a more searching scrutiny of the phenomena and a more varied application of interpretations, represents the higher limit of present reasonable aspiration. It is much too ambitious to hope for a demonstrative solution of the origin of the earth's glacial periods by first intention in the present state of knowledge.

The hypothesis here offered is not worked out into satisfactory detail at all points, but it is hoped that it is sufficiently matured to justify a preliminary statement. In forming it, which has been the work of several years, I have found, or seemed to find, the phenomena of past glaciation intimately associated with a long chain of other phenomena to which at

[1] A brief statement of the salient features of this hypothesis was given in a paper entitled A Group of Hypotheses Bearing on Climatic Changes, JOUR. GEOL., Vol. V, pp. 653–683, Oct.–Nov. 1897. For earlier history see footnotes on pp. 654 and 681 of that paper.

first they appeared to have no relationship. This chain led on and on until it became connected with many of the most fundamental problems of geology. When once an inquiry into the history of the atmosphere and its possible functions in the past was raised, there seemed no resting place until the origin of the atmosphere — and with it the origin of the earth — was reached. The inquiry raised profound skepticism regarding some of the most firmly accepted doctrines of the original state of the earth, its internal constitution, and the great dynamic forces that have controlled the larger phases of its history. A series of new, or partially new, hypotheses relative to these fundamental phenomena seemed to be necessary to fill out the group of alternative theories requisite to cover the ground of legitimate doubt based on specific reasons for doubt. In other papers I have given a partial expression to the hypotheses framed to cover these points.[1] The exposition of these has not in all cases been sufficiently ample to give them good working form, but has perhaps been sufficient to show their general relationship to an atmospheric hypothesis of glaciation.

The hypothesis here offered is confessedly connected in my own mind with these ulterior and more fundamental hypotheses, but it does not seem to me that it is necessarily so connected. To be sure, if it is assumed, following a prevalent custom of the past, that the original atmosphere was a vast gaseous envelope embracing essentially all the carbonic acid that is now locked up in limestone and other carbonates, and all that is represented by coal and other carbonaceous matter, and that the atmospheric history has been essentially a progressive depletion of this original supply, I do not see how the proposed hypothesis can be entertained, at least for the earlier glaciations. But if it be

[1] A Group of Hypotheses Bearing on Climatic Changes, JOUR. GEOL., Vol. V, No. 7, 1897. The Ulterior Basis of Time Divisions and the Classification of Geologic History, *ibid.*, Vol. VI, No. 5, 1898. A Systematic Source of Evolution of Provincial Faunas, *ibid.*, No. 6, 1898. The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *ibid*, Lord Kelvin's Address on the Age of the Earth as an Abode Fitted for Life, Science, N. S., Vol. IX, No. 235, pp. 889–901, June 30, 1899, and Vol. X, No. 236, pp. 11–18, July 7, 1899.

assumed that as early as Paleozoic times the atmosphere had some such constitution as it possessed in later geological times, and that its history has been a contest between the agencies of atmospheric supply and the agencies of atmospheric depletion, and that the constitution of the atmosphere at any time has been dependent upon the relative rates of supply and depletion, then the hypothesis may be entertained quite independently of all views of the origin of the earth and the atmosphere and of internal dynamics.

Previous advocacy of an atmospheric hypothesis.—The general doctrine that the glacial periods may have been due to a change in the atmospheric content of carbon dioxide is not new. It was urged by Tyndall a half century ago and has been urged by others since. Recently it has been very effectively advocated by Dr. Arrhenius,[1] who has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms deduced from observational data.[2] The great labor involved in this and the specific results springing from it place his contribution on a much higher plane than the general suggestions of those who had preceded him. Valuable as these general suggestions were, they must still be regarded as falling much short of working hypotheses, since no attempt was made to show that changes in the content of carbon dioxide of such a degree as would be compatible with the continuity of life and with other limiting geological conditions were quantitatively competent to produce the effects assigned them; nor were modes of inquiry into this essential matter suggested. It is one thing to point out a theoretical *causa vera*, and quite another thing to give good reasons for believing that it is quantitatively sufficient, and to open lines of inquiry for demonstrating that it is so. This Dr. Arrhenius has done and apparently with great success. While his results are doubtless to be regarded as subject to modification when more full and exact data are at hand,

[1] On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, by SVANTE ARRHENIUS, Phil. Mag., April 1896, pp. 237–276.

[2] See review of his paper in this number of the JOURNAL, p. 623.

it is apparent upon inspection that they can be very largely modified and still fall within the limits of the conditions of the case. This will perhaps appear more evident in the course of the subsequent discussion. In so far as the deductions of Arrhenius and the accompanying views of Professor Högbom [1] fail to definitely postulate operative geological agencies competent to produce the requisite variations in the constitution of the atmosphere, and to give reasons for believing that such agencies were in operation at the times requisite to produce the effects assigned them, they fall short of furnishing an ample working hypothesis from the geologist's point of view. This, of course, is the function of the geologist rather than the chemist and the physicist. Professor Högbom has made a valuable contribution to the general doctrine of consumption and supply.

To form a good working hypothesis in a geological sense, it is furthermore necessary to assign subsidiary agencies working in an oscillatory manner correspondent with the oscillations of glaciation now so well authenticated by observation.

Specific requisites of a working hypothesis.—It is obvious that it is necessary at the outset to assign agencies capable of reducing the amount of the carbon dioxide of the atmosphere at the time of the glaciations. If there were no other glaciation than that of the Pleistocene period, and if there were no kindred phenomena needing to be elucidated at the same time, it might be sufficient to point to the well-known abstraction of carbon dioxide from the atmosphere in the formation of limestones and carbonaceous deposits, and there rest the case, with the implication that further production of limestones and carbonaceous deposits would insure further glaciation, and that the permanent and final winter of the earth is at hand. A very slight computation of the rate at which carbon dioxide is now consumed is sufficient to show that an effective depletion of the atmosphere is near at hand unless there be sources of supply approximately equal to the depletion. But recent depletion touches only the

[1] Svensk Kemisk Tedskrift, Bd. VI, p. 169 (1894). Quoted in Dr. Arrhenius's paper, p. 269.

easier part of the problem. Whatever may be thought of the supposed signs of cold periods at other early periods, the evidences of glaciation in India, Australia and South Africa near the close of the Paleozoic era are so abundant, so specific, and so well attested, that they cannot be ignored, and any hypothesis that assumes to account for glacial periods must take serious cognizance of these and must meet the strenuous issues that spring from their early age and from the mildness of the periods following them. It seems to the writer almost equally necessary to take cognizance of the salt and gypsum deposits of various periods, which imply degrees of aridity in relatively high latitudes scarcely equaled at the present day. If the atmospheric line is followed, it seems necessary to postulate a reduction of carbon dioxide near the close of the Paleozoic era — to say nothing of other early times — so effectual as to produce glaciation between 20° and 35° latitude on both sides of the equator, a glaciation the deposits of which aggregate a greater thickness than those of Pleistocene times, and whose oscillations, marked by thick accumulations of coal, were even more remarkable than those of the Pleistocene glaciation. If a depletion of the carbon dioxide of the atmosphere sufficient to produce this glaciation at this relatively early stage in geological history is postulated, it is necessary to assign agencies for the reënrichment of the atmosphere in carbon dioxide to account for the mild climates in high latitudes in Jurassic, Cretaceous, and Tertiary times. In short, it is necessary to assign competent operative geological agencies which shall produce effective depletion alternating with effective reënrichment of the atmosphere from an early period in its history down to the present time. If the salt and gypsum deposits, and the prevailing red beds, with arkose elements, be regarded as the products of exceptional aridity, and if this be assigned to the localization and intensification of heat and moisture due to the removal of carbon dioxide, as subsequently set forth, it is necessary to multiply the oscillations from enrichment to depletion very notably, and to extend the alternating action at least as far back as the close of the Silurian period

when the great saline deposits of New York, Ontario, Ohio, Michigan and adjacent regions were laid down.

Primary assumptions.— (1) It is therefore assumed as the working basis of the hypothesis that the carbon dioxide of the Paleozoic atmosphere was at certain stages not essentially greater than it is today, that at the specific epochs of great saliferous deposition and of glaciation it was reduced to a quantity notably less than the present content, while at other and intervening stages its amount exceeded the present content by some multiple —these latter periods being those in which the wide extension of marine epicontinental life took place. For myself, I am disposed to extend the assumption of a measurably limited atmosphere back to the very beginning. To this I am led in part by the conviction that the gravitation of the earth is incompetent to hold an atmosphere very greatly beyond the amount so assumed, and by the much more speculative consideration that the earth may have grown up by slow accretion rather than rapid concentration, and that hence the early development of the atmosphere was controlled by limitations much like those that have affected it in its later history. But, as already remarked, this assumption is not regarded as vital to the hypothesis. (2) Wrapped up in the foregoing postulate is an assumption of the essential correctness of the doctrine of Arrhenius that variations of the atmospheric carbon dioxide falling within limits compatible with life and with other geological phenomena, are competent to effectively change the thermal state of the atmosphere. This needs further statement.

The functions of carbon dioxide.— By the investigations of Tyndall,[1] Lecher and Pretner,[2] Keller,[3] Rœntgen,[4] and Arrhenius,[5] it

[1] Heat as a Mode of Motion, 6th ed., pp. 345–349, 1892. Contrib. to Mol. Physics, pp. 38. 117, 421, 1888.

[2] Sitzungsberichte des Akad. der Wissenschaften d. Wien (2). Vol. LXXXII, p. 851 (2), Vol. LXXXVI, p. 52.

[3] Am. Jour. Sci. (3), Vol. XXVIII, p. 190.

[4] Poggendorfs Annalen (2), Vol. XXIII, p. 1259.

[5] Phil. Mag., Vol. XLI, pp. 237–279.

A brief statement of the conclusions of these authors is given in the article of Mr. Tolman in this number, p. 586. See also his review of Dr. Arrhenius, p. 623.

has been shown that the carbon dioxide and water vapor of the atmosphere have remarkable power of absorbing and temporarily retaining heat rays, while the oxygen, nitrogen, and argon of the atmosphere possess this power in a feeble degree only. It follows that the effect of the carbon dioxide and water vapor is to blanket the earth with a thermally absorbent envelope. Their absence would leave the surface of the earth essentially exposed to the free impact and free radiation of the solar rays, measurably, though of course not entirely, as if the earth were devoid of atmosphere. A reduction or an increase in these constituents would produce corresponding partial effects. The general results assignable to a greatly increased or a greatly reduced quantity of atmospheric carbon dioxide and water may be summarized as follows:[1]

a. An increase, by causing a larger absorption of the sun's radiant energy, raises the average temperature, while a reduction lowers it. The estimate of Dr. Arrhenius, based upon an elaborate mathematical discussion of the observations of Professor Langley, is that an increase of the carbon dioxide to the amount of two or three times the present content would elevate the average temperature 8° or 9° C. and would bring on a mild climate analagous to that which prevailed in the Middle Tertiary age.[2] On the other hand, a reduction of the quantity of carbon dioxide in the atmosphere to an amount ranging from 55 to 62 per cent. of the present content, would reduce the average temperature 4° or 5° C., which would bring on a glaciation comparable to that of the Pleistocene period.

The amount of moisture in the atmosphere, other things being equal, is directly dependent upon the temperature, and the temperature in turn is dependent upon the amount of moisture in the atmosphere. This reciprocal dependence renders the aqueous

[1] The action has two phases that in an exhaustive exposition would need separate statement, (1) the absorption of solar rays before they reach the earth, and (2) the absorption of the rays radiated by the earth. The latter have longer wave-lengths on the average and are relatively much more affected by the constitution of the atmosphere.

[2] Dr. Arrhenius, loc. cit.

vapor a vacillating factor subject to the control of any other agency which increases or decreases the atmospheric temperature. Whenever therefore an increase of carbon dioxide raises the temperature, it increases the quantity of water vapor and this by its thermal absorption further increases the temperature and calls forth more vapor and this action and reaction continue in diminishing force until an equilibrium is established. A decrease in carbon dioxide decreases the temperature and thus lessens the water vapor, and this further lowers the temperature and inaugurates a reversed series of actions and reactions. Fluctuation in the quantity of carbon dioxide therefore is attended not simply by its own individual effects, but by these auxiliary effects also. The carbon dioxide becomes therefore the determinative factor, and the question of the thermal absorption of the atmosphere may be discussed for convenience as though it were solely dependent upon the fluctuations in the content of this constituent, although this will not be strictly exhaustive.

b. A second effect of increase and decrease in the amount of atmospheric carbon dioxide is the equalization, on the one hand, of surface temperatures, or their differentiation on the other. The temperature of the surface of the earth varies with latitude, altitude, the distribution of land and water, day and night, the seasons, and some other elements that may here be neglected. It is postulated that an increase in the thermal absorption of the atmosphere *equalizes* the temperature, and tends to eliminate the variations attendant on these contingencies. Conversely, a reduction of thermal atmospheric absorption tends to *intensify* all of these variations. A secondary effect of intensification of differences of temperature is an increase of atmospheric movements in the effort to restore equilibrium. Increased atmospheric movements, which are necessarily convectional, carry the warmer air to the surface of the atmosphere, and facilitate the discharge of the heat and thus intensify the primary effect. In the case of a naked earth, the radiant energy of the sun falling directly upon the tropical belt is concentrated in space, and subject to the minimum reflection; in high latitudes, the rays

are spread over greater space, and are subject to greater relative reflection because of the low angle of incidence. In the case of an earth swathed in a thermally absorptive mantle, the direct equatorial ray is absorbed in traversing the atmosphere to a less extent than the ray of higher latitudes because it penetrates a less depth of atmosphere, while the amount of reflection from the atmosphere is small in both cases, so far as the transparent elements are concerned. In so far therefore as the temperature effects are dependent upon the absorption of the incoming rays, the greater depth of atmosphere penetrated in the higher latitudes makes important compensation for obliquity of incidence.

In the case of a naked earth, or an earth clothed with a non-absorptive atmosphere, the solar rays which are tangential to the polar regions have no heating influence upon the earth, while in the case of an earth clothed with an absorbent atmosphere, similar rays are partially absorbed, and serve to warm the earth. In the polar regions, therefore there is a very radical difference between the effects of an absorbent and a non-absorbent atmosphere. The same holds true of the heating effects of the morning and evening sun. With a non-absorbent atmosphere, the tangential morning and evening rays pass through and are lost; in a thermally absorbent atmosphere, they are effectually retained.

In so far as the incoming rays are absorbed in the atmosphere their immediate effects are chiefly felt in its upper strata and their influence upon the surface of the earth is lessened. This is due to the fact that the upper regions are penetrated by rays of all the various wave-lengths that emanate from the sun, while the lower portions are penetrated only by such rays as are left after the selective absorption of the upper atmosphere. The degree of this absorption of the rays of long wave-lengths is such that comparatively little further absorption takes place in the basal portion of the atmosphere, according to the interpretations of Arrhenius. One effect of increasing the absorptive capacity of the upper air by increasing the amount of carbonic acid is an increase in the elevation of the strata chiefly heated by the

incoming rays and the consequent reduction of the thermal gradient of a vertical column of the atmosphere. As a result there is less effective tendency to convection and less discharge of heat from the atmosphere.

In high latitudes, besides this effect, it is also to be noted that with an increase of the absorptive capacity of the upper atmosphere, rays that previously passed through the higher strata with little absorption are arrested and contribute heat to the upper air. The same is true of morning and evening rays at high elevations.

In the case of the outgoing rays, which are absorbed in much larger proportions than the incoming rays because they are more largely long-wave rays, the tables of Arrhenius[1] show that the absorption is augmented by increase of carbonic acid in greater proportions in high latitudes than in low; for example, the increase of temperature for three times the present content of carbonic acid is 21.5 per cent. greater between 60° and 70° N. latitude than at the equator. The maximum thermal effects also lie in higher latitudes for the summer months than for the winter months. On the other hand, when the carbonic acid is reduced to 0.67 of the present content, the maximum winter variation is felt between 30° and 40° N. latitude. If the carbonic acid be further reduced, the maximum variation found by extrapolation falls at and below 30°, the latitude of the Carboniferous glaciation. It is not intended, however, to imply that this would be sufficient in itself to produce that glaciation.

An atmosphere having a relatively large percentage of carbon dioxide and water, *i. e.*, an absorptive atmosphere, has a higher heat content than a non-absorptive one, and its circulation in latitude more effectually equalizes the temperature with the same degree of movement.

Similar considerations are applicable to the effects of land and water areas. In so far as the atmosphere absorbs the incoming rays in passing through it, the amount that reaches the surface of the earth is reduced. To this extent the possibility of

[1] Loc. cit., p. 266.

differential effects between the sea and land is lessened. On the other hand, in the absence of absorptive and diffusive effects, the tropical rays fall with full intensity upon the surface. On the land they promptly heat the immediate surface, and the heat is as promptly radiated away. On the sea, neglecting reflection, they penetrate deeply into the water until they are absorbed. The upper layer of the sea is therefore heated to a notable depth, and radiates its heat away with relative slowness. The result is an intensification of the differences in average temperature of the land and the sea. This action is quite familiar, but perhaps not the point here urged—that this difference is dependent on the atmospheric effects upon the incoming as well as outgoing rays. If the atmosphere were so far robbed of its absorbent factors, carbon dioxide and water, as to give great intensity to this differential effect, the result might be an average temperature of the land below the freezing point, while that of the sea might be relatively warm. It seems clear that at some point short of an absolute thermal transparency a stage would be reached where the average temperature of the land would sink below zero, while yet the sea, barring convection in latitude, would retain a comparatively mild temperature. There would then apparently arise, even in low latitudes, the conditions of glaciation.

Without following out these lines into greater detail, the more pertinent deductions may be summed up in the following propositions: A reduction of the thermal absorption of the atmosphere would intensify the differences of temperatures between (1) the basal and the upper portions of the atmosphere; (2) low and high latitudes; (3) land and sea; (4) night and day; and (5) the seasons. In short, it would intensify temperature differences generally, and would lead to (1) greater local heat, as well as greater local cold; (2) to greater local dryness, as well as greater local moisture; (3) to more intense movements of the atmosphere in the endeavor to maintain equilibrium; and (4) to lower average temperature. The effect of reducing the absorbent factors is the intensification of differences.

On the other hand, an increase in the absorptive factors renders ineffectual, in a corresponding degree, the variations of altitude, of latitude, of land and sea, of day and night, and of the seasons, and conduces to an equable and mild temperature, to gentle and yet thermally effective circulation, and to higher average temperature. As Arrhenius has remarked, "The geographical, annual, and diurnal changes of temperature would be partly smoothed away if the quantity of carbonic acid was augmented. The reverse would be the case (at least to a latitude of 50° from the equator) if the carbonic acid diminished in amount."[1]

AGENCIES OF DEPLETION AND ENRICHMENT

It now becomes necessary to assign agencies capable of removing carbon dioxide from the atmosphere at a rate sufficiently above the normal rate of supply, at certain times, to produce glaciation; and on the other hand, capable of restoring it to the atmosphere at certain other times in sufficient amounts to produce mild climates.

These agencies on both sides belong to two classes, the permanent and the temporary, and the distinction has practical importance.

Sources of permanent loss.— Permanent depletion results from the consumption of carbon dioxide in the transformation of the silicates of the original earth, and of volcanic products into the carbonates of the secondary strata. It is fairly safe to assume that the original earth's surface was composed of material of the general class represented by the igneous rocks and the basement complex. These, it is needless to say, consist largely of silicates with which are associated certain quantities of certain gases to be considered more fully hereafter. These silicates, where exposed to the weathering action of the atmosphere, become decomposed and take the form of carbonates (with less quantities of sulphates, phosphates, etc.) and of residual silicates and oxides (kaolin, quartz, ferric oxides, etc.). Neglecting the minor transformations which do not concern us here, the operation may be

[1] Loc. cit., p. 268.

characterized as carbonation, and consists essentially of the substitution of carbonic acid for the silicic acids. The carbonic acid is derived, in the main, from the atmosphere. In their soluble condition, the carbonates so formed are largely bicarbonates. This is the only form in which calcium carbonate is appreciably soluble, and the same is true in a less degree of magnesium carbonate. The monocarbonates of potassium and sodium are highly soluble, but the bicarbonates also appear in solution. Practically the carbonates of these alkalis usually become changed into other salts (sulphates, chlorides, etc.) and the carbon dioxide that may have been temporarily locked up with them is set free by the change, or enters some other combination. The magnesium and calcium carbonates are also in part changed to other salts. But for the purposes of this discussion, which is concerned chiefly with the final issue and not with the transient stages of these compounds, it is sufficient to note that the chief result of the decomposition of the original silicates is the formation of calcium and magnesium carbonates, which are deposited as limestones and dolomites and thus lock up carbon dioxide at the expense of the atmosphere. The amount so taken from the air in the known geological periods has been variously estimated at from 20,000 to 200,000 times the present content; indeed estimates have gone beyond the last figure. When it is considered that 44 per cent. of all pure limestone and a higher per cent. of all pure dolomite is carbon dioxide, it is obvious that the total quantity is very large, and its computation is dependent upon the estimate of the total amount of limestone and dolomite in the crust of the earth.

A second source of permanent loss consists of the consumption of carbonic acid by plants and the fixation of the carbon in carbo-hydrates, hydro-carbons and other carbonaceous compounds which ultimately take the form of coals, bitumens, oil, gas, and perhaps most important of all, disseminated organic matter in the sedimentary series.

Exceptions.—Some hydro-carbons have probably been produced by inorganic action, notably those derived from carbides

(Moissan) formed within the earth and extruded from it. Some carbonates probably have been formed by carbonic acid contained within the rocks or extruded from the interior. In certain phases of the problem, deduction is to be made for such carbonaceous compounds and carbonates as are formed in the sea by marine plants and other agencies which derive their carbonic acid from the sea water; but in the general discussion of the question, the carbonic acid of the sea must be reckoned in with the carbonic acid of the air, for the two are in equilibrium and constitute essentially and potentially one body. The necessity for this assumption will be more obvious when we come to discuss the function of the ocean in influencing the constitution of the atmosphere.

Sources of permanent gain.—Over against these sources of secular loss there are certain sources of gain. If the assumption that the constitution of the atmosphere has varied through only moderate limits within the known ages be adopted, it is necessary to postulate sources of supply of a competency approximately equal to the sources of loss. The data for such postulation are exceedingly unsatisfactory and a function of the hypothesis should be to stimulate investigation in these lines which have been barely touched by serious inquiry.

a. Gain from the interior.—The crystalline rocks of the surface of the earth have been shown by the recent examinations of Tilden [1] to contain very notable quantities of gas, consisting of hydrogen in preponderance, carbon dioxide and carbon monoxide in large percentages, and nitrogen and marsh gas in small quantities, with water vapor, but with a practical absence of oxygen. Twenty-five analyses, including ancient and modern volcanic and even some metamorphic rocks, gave an average volume of gas equal to about four and a half times the volumes of the containing rocks. A computation on this basis shows that an atmosphere equivalent in mass to the present one would be contained in a very superficial rind of the earth, and that if this volume of

[1] On Gases Contained in Crystalline Rocks and Minerals: W. A. TILDEN, Chemical News, April 9, 1897.

included gases be constant for the whole body of the earth, it contains potentially a multitude of atmospheres.

It is a familiar fact that enormous quantities of gases are ejected from volcanoes during their active periods. It has been very generally assumed that these gases and vapors, among which steam vastly preponderates, have a surface origin, and there can be no doubt that this is true of some notable part; but, on the other hand, there is abundant ground for the belief that another notable part is brought from the interior and is a real contribution to the earth's atmosphere and hydrosphere. It may not be possible at present to demonstrate this, but inquiry in this direction is invited. There seem to be no means of estimating from present data even approximately the volume of gas which is given forth, but it is certainly large. There are grounds for believing that the gases of the interior escape by other than volcanic vents. The deep rending and sharp shock of the earth in seismic movements, the stresses and fissuring of readjustments, the disintegration of crystalline rocks, and the resources of slow diffusive penetration are among these. So far as the setting free of carbon dioxide by decomposition of the containing rock is concerned, it is to be noted that the chemical action which sets it free involves a consumption of carbon dioxide very greatly in excess of the amount liberated, so that, as computation will show, the total effect of the process is one of loss which the internal gases only very slightly modify. This, of course, is not true of mechanical disintegration.

b. Exterior sources of gain.—The meteorites which are constantly falling to the earth contain included gases, often in great volume. They also contain carbonaceous matter which is partially burned in passing through the air. The nature of the included gases is notably similar to those of the crystalline rocks, hydrogen and carbon dioxide being the leading constituents with nitrogen in very subordinate amount and free oxygen essentially absent.[1] Water vapor appears in both meteorites and

[1] See numerous papers of A. W. WRIGHT in Am. Jour. Sci., notably Gases contained in Meteorites, Am. Jour. Sci, 3d series, Vol. XII, No. 69, Sept. 1876.

crystalline rocks, but it is impossible to say how far it was absorbed from terrestrial sources. It has even been suggested that all the gases both of meteorites and of the crystalline rocks were simply absorbed from the air and not brought in from without; but their proportions are so different from those of the air that it would be necessary to assume an extraordinary selective power to make this possible; for oxygen must be wholly rejected as a gas; nitrogen, though greatly preponderant, must be almost neglected; carbon dioxide must be absorbed in great quantities relatively; carbon monoxide, though very rare in the atmosphere, must be taken in abundantly; while the hydrogen, which is scarcely detectable in the atmosphere, must be absorbed in superlative amounts. It is difficult to conceive how a meteorite passing rapidly through the air can have absorbed many times its volume of an element which does not appear in the air in detectable quantities. However, I am unable to say that the analyses were made sufficiently soon after the fall of the meteorites to make this point conclusive. But, at any rate, the hypothesis of selective absorption is confronted with grave difficulties and the alternate hypothesis that the gases are brought to the earth in the meteorites seems the more probable. The emanations from comets support the view that meteorites are charged with gases in extra-terrestrial regions. Here again inquiry is needed and experimental tests are obviously suggested.

If gases are brought in with meteorites, it is probable that independent molecules are flying through space and are caught up by the earth. The modern doctrine of molecular velocities, which holds that gases are liable to escape, and presumably are escaping constantly, from planetary bodies, carries the presumption that individual molecules are flying through space with some degree of frequency. Astronomical phenomena, to be sure, seem to indicate that the quantitative value of these cannot be very great, but as definite data are yet wanting and we are dealing with vast lapses of time and slow processes of depletion, making need for slow processes of accretion only, this agency may

deserve a place among the undetermined sources of atmospheric material.

It is among the possibilities that the sun itself may be a direct source of atmospheric feeding. The speed at which the solar prominences are projected from the sun has been observed to exceed the parabolic velocity of the sun;[1] that is, the rate of projection is such that if the outer atmosphere of the sun does not effectually interfere, the gases are shot away beyond even the sun's control. A much less speed could carry the gases to the earth, so that, unless the outer atmosphere of the sun interposes effectual barriers, it is not improbable that gases are thrown as far out as the orbit of the earth. The earth probably cannot hold hydrogen, the chief gas of these prominences, permanently as such, but it may do so when combined with oxygen. The shooting of solar hydrogen through our atmosphere would lead to the formation of water, because, even at ordinary temperatures, such of the molecules of oxygen and hydrogen as collided with the requisite velocity would enter into union. There seem therefore grounds for placing this among the possible but undetermined sources of supply for our atmosphere and hydrosphere. When the mystery of the zodiacal light and the gagenshein shall be solved, it is possible that demonstrative evidence of our relations to the extreme projections of the solar atmosphere may be available.

In the present state of extreme uncertainty relative to all these possible sources of supply, a hypothesis which necessarily involves them proceeds with uncertain steps and must perforce wait patiently for more definite determinations, but the pressing of a hypothesis which lays emphasis upon them is but giving effect to the fundamental mission of all working hypotheses.

VARYING RATES OF ACTION

By the terms of the hypothesis the state of the atmosphere at any time is dependent upon the relative rates of loss and gain.

[1] The Story of the Sun, by SIR ROBERT BALL, pp. 185–188; The New Astronomy, LANGLEY, p. 61.

It is of supreme importance therefore to consider irregularities in the action of the sources of loss and gain.

Varying rates of gain.—The constancy or irregularity of the sun's contribution—assuming it to make a recognizable contribution—is quite unknown. It would presumably be dependent upon the internal explosive action of the sun concerning which all thought is as yet highly speculative. So far as its relations to geological periods are concerned, it would probably be either an essentially constant factor or one which would not fall in systematically with any special phase of geological progress, and could not be regarded as a coöperative factor in any definite phase. It might be progressively increasing, as the sun concentrates, or progressively diminishing.

Much the same is to be said with regard to possible sources of supply from meteoric and similar extra-terrestrial sources.

The extrusion of gases and vapors from the interior has been presumably periodic, because the conditions of molten eruption and of mechanical disruption have probably been periodic rather than constant. No specific determination of the periodicity of volcanic action has yet been made out, but the testimony of present geological data is to the effect that vulcanism has been more frequent and intense at certain periods than at others. This is clearly true for individual grand divisions of the earth, and seems to be true of the earth at large, notwithstanding the fact that vulcanism was a more or less local phenomenon. While a definite periodicity, specifically connected with other phenomena, cannot now be affirmed, the tentative proposition that vulcanism has been more abundant in great periods of readjustment than in periods of quiescence may be entertained. The connection with those periods seems sometimes to have been very intimate and immediate, and at other times more remote. So far as disruption of the rocks constitutes a means of escape for internal gases, there should obviously be a close connection with periods of readjustment. In a rather general and uncertain way, then, it would seem necessary to assume, in a working hypothesis, that the enrichment of the atmosphere from internal

sources has proceeded more rapidly at or about the periods of crustal disturbance. This, as we shall see, coincides practically with the periods of depletion from atmospheric action on the surface, and hence, so far forth, the two processes tend to neutralize each other and preserve the constancy of the earth's atmosphere. The hypothesis must therefore recognize that it was only when one agency fell behind the other in its competency that its specific results became manifest, and then only by the difference in their respective effects.

Varying rates of loss.—The rate of chemical action of the atmosphere on the surface of the rocks is believed to have been intimately connected with the extent and height of the land area, considering the earth as a whole. There were qualifying conditions, as we shall see, but notwithstanding, this is regarded as an important law. It is made a fundamental postulate of the hypothesis, and the vitality of the hypothesis as a working instrument of investigation hangs very largely upon it. It is obvious that the greater the surface area of rock exposed to the effective action of the atmosphere, the more rapid will be the rate of disintegration, other things being equal, and the more rapid the consumption of carbon dioxide. [1]

The rate of carbonation of the rock is dependent upon elevation as well as superficial area. The disintegration of rock is the most active by far in the zone lying between the surface and the level of permanent underground water, technically the water table. It is in this zone that the atmosphere and the moisture of the earth combine to give the greatest chemical

[1] Oxygen is also consumed in the decomposition of average rock, but in less amount than carbonic acid, and as the amount of oxygen in the air is very much larger than that of carbon dioxide, the part consumed is far less critical. In an exhaustive study of the constitutional history of the atmosphere, the loss and gain of oxygen must be considered, and certain very interesting and important phases of atmospheric variation are probably connected with the production and consumption of the oxygen, but, as indicated, they are much less immediate and critical in the consideration of thermal problems with which our hypothesis is more especially concerned, and for the sake of simplicity the oxygenation of the rocks may be temporarily neglected; and for like reasons the many minor reactions may also be ignored and attention confined to the carbonation.

activity. It is established by the most ample observation in mining, that below the permanent water level disintegration has made slow progress compared with that in the zone above the water level. Now the thickness of the zone between the surface and the permanent water level is intimately dependent upon the general altitude. In a continent reduced approximately to base level, this zone is exceedingly thin. In a region much elevated and deeply dissected by erosion, the thickness of the zone is very much greater. As between a continent with an average elevation of 2000 feet, at the climax of dissection following a crustal readjustment, and a continent of similar area with an average elevation of 300 feet, during a period when it is approximately at base level, the average depth of the aërated zone above the water level, probably varies more nearly with the square of the elevation than as a direct multiple of it. It is improbable, however, that the chemical action is augmented at so great a ratio. Probably greater warmth and more abundant vegetation are correlated with the lower altitudes, and both these aid chemical action. This in turn is somewhat offset by the greater mechanical disaggregation which results from changes of temperature and from gravitative influence in the more elevated condition. Making all allowances that seem required for the offsetting factors, it would still appear that the elevated condition increases the activity of decomposition in a very notable degree.

Below the permanent water level, the advantage probably also lies greatly with the higher elevation. The action of surface water upon the deeper rock is dependent upon the unbalanced hydrostatic pressure which promotes underground circulation and forces the water through the crevices and pores of the rock. If the underground water stands near sea level, there is little unbalanced hydrostatic pressure to promote active circulation and thereby carry the surface waters, enriched with atmospheric gases, down into the lower strata and bring them into action. The atmospheric waters precipitated upon the surface run away chiefly at the surface, and fail of the contact necessary for action. On the other hand, in an elevated region

there is a potential hydrostatic pressure measured by the difference of altitude of the surface of the ground water and the surface of the sea which tends to cause the waters to flow through the rock and thus find a tortuous way to the equilibrium of the sea level. A deep underground circulation is therefore a function of high altitude, and, correlated with that circulation, is chemical activity proportionate to the enrichment of the surface waters with chemically active agencies, in the present instance, carbon dioxide in particular. This deeper circulation, correlated with hydrostatic pressure, is enhanced by the greater degree of fissuring of the rock which attends elevated tracts, for in the process of elevation, writhing and cracking are notable incidents, and, in addition to this, the gravitative tensions which necessarily attend an elevated position lend their aid in the production and opening of crevices. Precisely the opposite conditions prevail at low levels. The protruding superficial portion of the land is the most fissured part and when it has been cut away by erosion the basal remnant is normally less open to the penetration of water. It would appear from a consideration of these several associated influences that disintegration and decomposition are facilitated by elevation in a very important degree.

If, therefore, there were times in the history of the earth when there were general readjustments of its bodily form to accumulated internal stresses, resulting in extensive elevations, embracing not only the formation of mountains and plateaus, but the general warping outwards of the continental platforms, and the bowing downwards of the ocean basins, attended by the withdrawal of the sea, so that the land area was extended and, at the same time its average elevation increased, and a portion of it rent and crushed, it is believed that the carbonation of the rocks must have been accelerated by some notable multiplier and that the rate of consumption of the carbon dioxide of the atmosphere must have been correspondingly promoted ; and this is made an important postulate of the hypothesis.

At least two periods of such very general and notable

elevation appear to be well authenticated by present geological data, imperfect as they are for certain quarters of the earth. These periods occurred near the close of the Paleozoic and of the Cenozoic eras respectively. Closely connected with these two periods are two well authenticated glacial periods.

If, on the other hand, there were periods of prolonged quiescence of the earth's body during which the lands were cut down well towards base level, they would be accompanied by a progressive slackening of the rate of disintegration, and a corresponding reduction in the rate of atmospheric loss of carbonic acid, giving opportunity for the agencies of repletion to overtake and surpass the agencies of depletion. It is believed that there was a series of such periods among which the Cretaceous is best authenticated.

During a prolonged period of relative quiescence the encroachment of the coast lines upon the land, if elevated, becomes notable. In addition to this, the material removed from the land and deposited in the sea raises the water level, and when the degradation is notable this rise amounts to an appreciable factor. This aids the coast action by lifting it above the restraining influences of its own products, which, by shoaling the water off shore, tend to break the force of wave action. The notion is also entertained that during periods of readjustment the continental masses are apt to be lifted beyond the plane of perfect isostatic equilibrium, and that there follows a tendency to slowly creep back into equilibrium, accompanied by a general tendency of the continental platform to flatten out under gravitative stress. The continental platforms are to be regarded as having elevations above the abysmal ocean bottom of perhaps 12,000 feet, and, as their average gravity is two and a half to three times that of the water which surrounds them, there remains a large excess of gravitative stress tending to cause the continents to spread laterally.

The combined effects of these agencies is a transgression of a thin edge of the sea upon the land. Now, such extensive transgression took place on all the great continents in the Upper

Cretaceous period, and this fact may be taken as indicating that the planation which reached so pronounced an expression on the American continent at that period affected nearly or quite all the continents in some similar measure. An inspection of the whole range of geological history shows periods of similar transgression accompanied by the development of luxurious and cosmopolitan marine faunas of the shallow-water type which in themselves imply the conditions here postulated.[1]

If this be a correct view it is obvious that at such periods the areas of land exposed to atmospheric action were notably reduced by sea encroachment, and that at the same time the lowness of the land greatly limited the depth of atmospheric activity by reducing the zone between the surface and the water-table and by reducing the hydrostatic penetration of surface waters. As already remarked, there is to be counted in offset probably warmer temperature, a higher degree of moisture, and a more abundant vegetation, but it is not believed that this approaches, even remotely, to a full offset to the reduction due to low elevation and reduced area.

If the foregoing views are correct there were certain periods in the history of the earth when carbonation proceeded with multiplied activity, separated by other periods during which its activity was greatly reduced. The intensification and the reduction differ by some notable multiplier of the average rate.

In working application, the hypothesis tentatively recognizes as periods of land extension attended by rapid carbon dioxide consumption, (1) the close of the Silurian and the opening of the Devonian, (2) the Permian and early Triassic, and (3) the Pliocene and Pleistocene. To this category may perhaps also belong, though the evidence at present is less adequate, (4) the early Cambrian, (5) the closing Ordovician and opening Silurian,

[1] For further statement of these views, see The Ulterior Basis of Time Divisions and the Classification of Geologic History, JOUR. GEOL., Vol. VI, No. 5, July–August, 1898, pp. 449–462; A Systematic Source of Evolution of Provincial Faunas, JOUR. GEOL., Vol. VI, No. 6, Sept.–Oct., 1898, pp. 597–608; The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *ibid.*, pp. 609–621.

(6) the close of the Jurassic and the opening of the Lower Cretaceous, and (7) the transition period between the Cretaceous and the Eocene. In these periods there are evidences of declared intensifications of climatic influence expressed in widespread and thick deposits of salt and gypsum and in great series of red sandstones and marls, and, in the two most notable cases, by pronounced glaciation in middle and low latitudes.

On the other hand, it regards the following as periods of sea extension attended by the active freeing of carbon dioxide through the agency of prolific lime-secreting life, as hereafter set forth: (1) the middle Ordovician, (2) the middle Silurian, (3) the sub-Carboniferous, (4) the late Jurassic, (5) the Upper Cretaceous, and (6), less notable, the later Eocene and earlier Miocene. During these periods there is evidence of extensive limestone deposition spreading out widely on the continental platforms, attended by very mild and equable climates very nearly uniform for all latitudes.

SOURCES OF TEMPORARY LOSS AND GAIN

The discussion has thus far taken note of the original carbonation of the silicates of crystalline rocks only. These crystalline rocks, according to Dr. Tillo,[1] occupy something over 20 per cent. of the surface of the land. There remains nearly 80 per cent. occupied by secondary rocks which now claim attention.

Sources of temporary loss—The function of the secondary deposits.—To a large extent the material of the secondary deposits underwent chemical decomposition and carbonation preliminary to its deposition, indeed as a prerequisite to its derivation. In so far as this process was incomplete in the earlier stages, it was continued during any subsequent state of exposure, but this action belongs under the preceding head of original carbonation.

In the erosion of tracts of secondary rocks the limestones and dolomites are dissolved and carried down to the sea essentially as bicarbonates. In the strata they existed as monocarbonates. Their solution involves the taking up of a second

[1] Berghaus Atlas.

equivalent of carbonic acid to render them bicarbonates, and this second equivalent is derived essentially from the atmosphere. There is herein a source of temporary loss, temporary because the second equivalent of carbon dioxide remains associated with the bases in the sea only until deposition takes place, when it is set free. It is to be noted that a second equivalent is also taken up in the formation of original carbonates if they are dissolved. As the crystalline rocks occupy only a little more than 20 per cent. of the land surface and are probably not removed as fast as the secondary rocks, not more than about one fifth, probably not more than one tenth, of the bicarbonating carbon dioxide is associated with original carbonation. The remaining four fifths or more are occupied in bicarbonating and dissolving the calcareous and magnesian portions of the secondary rocks. It follows that the ratio of carbon dioxide now taken out of the atmosphere as second equivalent in any unit of time, to that taken out as first equivalent, is probably fully five to one, and not unlikely as high as ten to one. This ratio would not necessarily hold for past periods, but in all those under consideration the second equivalent was undoubtedly very much greater than the first.

Accepting, for the purposes of a rude estimate, the data of T. Mellard Reade,[1] the amount of carbon dioxide removed annually by original carbonation, reckoned by proportional area, is 270 million tons, the amount temporarily removed as the second equivalent of the bicarbonates is 1350 million tons; the amount simply transferred from the land to the sea as the first equivalent of the carbonates previously formed is 1080 million tons; the total mass taken from the atmosphere annually being therefore 1620 million tons, and the total mass removed to the sea 2700 million tons. Besides uncertainties in the original estimate of Reade, the first item is subject to correction (probably large) for the slower rate of disintegration of the crystalline rocks. This is, however, somewhat offset by weathering action on the silicates that remain undecomposed in the secondary rocks, and on

[1] Addresses, Geol. Soc. of Liverpool, 1876 and 1884, quoted in Dana's Manual, p. 191.

the late volcanics which are not all included in the 20 per cent. of the land area reckoned as crystalline. The second item is subject to correction to the extent that the salts were normal carbonates and not bicarbonates.

Reciprocal sources of temporary gain.—The second equivalent of the carbonates in the ocean is subject to easy removal under suitable conditions, and reënriches the atmosphere by diffusion into it from the ocean. The conditions under which this is set free are of critical importance to our hypothesis. We have to consider (*a*) saturation, (*b*) chemical reactions and dissociations, and (*c*) organic action.

a. Absence of general saturation.—In the absence of other agencies of removal the accumulation of calcium bicarbonates in the ocean would go forward to the point of saturation, if there were a sufficient amount producible. It would then be deposited as limestone, and the second equivalent of the carbon dioxide would be set free. There is little reason to think, however, that general saturation has been reached during the known portion of the earth's history. In local basins subject to peculiar conditions, saturation certainly has been attained, as the marls of the great saliferous deposits testify. The present approach to oceanic saturation in calcium carbonate is apparently only about 40 per cent. If the ocean in former times had reached saturation in calcium carbonate and any notable precipitation had followed, the precipitate should appear as a distinctive constituent of the clastic deposits. While calcareous matter which might be so interpreted occurs in some of these deposits, there is a notable absence of anything of the kind in many others where it might be expected, and the general character of the sandstones and shales seems more concordant with the accepted view that they were laid down in waters that did not, except in special cases, directly deposit calcareous matter. In view of the probable presence of lime-secreting organisms, the problem is generally rather to account for the paucity of calcareous matter than its abundance in the clastic deposits. The explanation is doubtless found in the undersaturation of the sea water and its ability

to dissolve calcareous relics. This view is supported by the partially dissolved condition in which calcareous fossils are so commonly found in the sediments of practically all the ages. The inference, therefore, to be drawn from the character of the sediments, and from the partial solution of calcareous fossils, is that the ocean, as a whole, has not generally been saturated with calcium bicarbonate during its known history. Murray has made us aware that at the present time the greatest depths of the ocean dissolve calcareous relics so freely as to prevent their accumulation.

b. Inorganic chemical reactions. — Viewed comprehensively the sea water consists of such solutions as have been carried down from the land in past times, modified by concentration and deposition. No important constituent has been totally removed. The land and sea waters have therefore the same fundamental constitution, but the salts of the former enter the sea in a more dilute form and in different proportions from those contained in the latter. Aside from organic action, and from exceptional inorganic agents such as may arise from submarine volcanic action and like incidental sources, essentially all occasion for chemical reaction when land waters are added to sea waters, is limited to a readjustment of the equilibriums of the common constituents of the two commingling waters. Following the simple doctrines of the old familiar "chemistry of results," the addition of a dilute solution of salts of the alkalis and alkaline earths to a more concentrated but not saturated solution of the same salts would neither occasion precipitation nor the evolution of gas, for every acid is mated with a base, and all are much below the point of saturation. According to the old interpretation the bases of the sea salts are, in the main, mated to stronger acids than those of the land waters, and these combinations will not be changed on the entrance of the latter. So, also, the small amounts of strong acids of the land waters are already mated with the strong bases in the main, and largely form the same combinations as those of the sea waters. Such interchanges as follow involve a double reaction essentially without the freeing

of acid or base. Under the old method of interpretation the sea salts, according to Dittmar, consist of—

	Percentage	Total Tons
Sodium chloride	77.758	$35{,}990 \times 10^{12}$
Magnesium chloride	10.878	$5{,}034 \times 10^{12}$
Magnesium sulphate	4.737	$2{,}192 \times 10^{12}$
Calcium sulphate	3.600	$1{,}666 \times 10^{12}$
Potassium sulphate	2.465	$1{,}141 \times 10^{12}$
Calcium carbonate	0.345	160×10^{12}
Magnesium bromide	0.217	100×10^{12}
	100.000	$46{,}283 \times 10^{12}$

A rude average of the composition of land waters and of the amounts of salts carried to sea annually, founded on the estimates of T. Mellard Reade, is here given for comparison.

	Approx. percentage	Tons annually
Calcium carbonate	50	$2{,}700 \times 10^{6}$
Calcium sulphate	20	$1{,}080 \times 10^{6}$
Magnesium carbonate	4	216×10^{6}
Magnesium sulphate	4	216×10^{6}
Sodium chloride	4	216×10^{6}
Potassium and sodium, Sulphates and carbonates	6	324×10^{6}
Silica	7	378×10^{6}
Other substances	5	270×10^{6}
	100	$5{,}400 \times 10^{6}$

These tables do not embrace the second equivalent of carbonic acid.

From these data it appears that it would require only a little over eight and one half million years for the land waters to bring in a gross amount of salt equal to that of the ocean, but it would require very different periods to bring in the individual constituents. It would take 166 million years to bring down the sodium chloride, but only about 1.5 million years to bring down the calcium sulphate, and only about 60,000 years to bring down the calcium carbonate. It appears therefore that there must be agencies constantly removing the calcium carbonate and the calcium sulphate at relatively high rates. These particular figures are subject to all the uncertainties involved in

Reade's primary estimate, but they probably represent approximately the relative ratios, and show the general nature of the eliminations that are requisite to change accumulating land waters into sea waters.

While these general statements of the nature and limitations of chemical action, based on the more familiar doctrines of the older chemistry, are doubtless essentially true, the refinements of modern chemistry teach that there is an intricate series of dissociations and exchanges of acidic and basic factors, and of the various ions, in an effort to establish and maintain a new equilibrium between the salts, required by their new proportions and their new states of dilution. As the land waters contain a relatively large percentage of bicarbonates of calcium and magnesium, the readjustment affects these especially, with the result that probably a minor percentage of the second equivalent of carbon dioxide is set free. It seems necessary to state this with qualification on account of the extreme complexity of the reactions, and the incompleteness of existing data; but the Challenger, and similar investigations show that the quantity of second equivalent of carbon dioxide is less than sufficient to raise all of the carbonates into bicarbonates. This deficiency is apparently limited to 20 per cent. or less of the theoretical amount required. More rigorous experimental determination is, however, greatly needed.

It is probable that the second equivalent of the land waters is deficient in some like degree, but this has not been experimentally determined. If this be true, it must reduce the estimate of the carbon dioxide brought down to sea, and also the amount set free by dissociation. The total amount of carbon dioxide which may be supposed to be set free by inorganic reaction in the sea in its present state of concentration, is therefore probably much less than 20 per cent. It is obvious from the preceding considerations, and others that will follow, that to maintain the atmospheric status even approximately there must be a nearly or quite complete return of the second equivalent of carbon dioxide by some means. This is also implied by the fact that

the oceanic deposits are not bicarbonates in any notable degree. The chief agencies of this return are held to be organic, and will be considered presently.

The chief compounds of both the land and sea waters are sodium, potassium, magnesium and calcium chlorides and bromides; sodium, potassium, magnesium and calcium sulphates; sodium, potassium, magnesium and calcium carbonates and bicarbonates; in other words, every combination which may take place between the acids and bases involved. Besides these salts there are, theoretically at least, the several acids and bases and a complete series of ions as well. There is a continuous dissociation and reunion in the effort to maintain equilibrium. The extent of the dissociation is dependent, among other things, notably upon the degree of concentration of the solution and upon its temperature. In an especial degree the extent of the freeing of the second equivalent of carbon dioxide is believed to be dependent upon this dissociation as influenced by temperature, and it is thus a vital consideration in realizing the function performed by the ocean during glacial episodes when its temperature was greatly changed. This function is made the subject of a special study in the paper of Mr. Tolman in this number of the JOURNAL.[1]

Mr. Tolman's studies have been founded upon Dittmar's experiments, and seem to show that the amount of carbonic acid freed from the bicarbonates by dissociation is very sensibly influenced by such changes of temperature as are necessary, according to the deductions of Dr. Arrhenius, to produce extended glaciation, on the one hand, and a mild climate in the arctic regions, on the other. In this he finds support for the suggestion which I made in a previous paper[2] that the ocean during a glacial episode instead of resupplying the atmosphere, in the stress of its impoverishment, would withhold its carbon dioxide to a certain extent, and possibly even turn robber itself. On the other hand, when the temperature is rising after a glacial

[1] Pp. 585-618.

[2] A Group of Hypotheses Bearing on Climatic Changes, Vol. V, No. 7, 1897, p. 682.

episode, dissociation is promoted, and the ocean gives forth its carbon dioxide at an increased rate, and thereby assists in accelerating the amelioration of climate.

c. Organic action. — The elimination of the vastly preponderating percentage of calcium salts in the land waters, involving a reduction from 70 per cent. in these to less than 4 per cent. in sea waters, is assigned mainly to marine life. With the calcium sulphate we do not seem to be specially concerned here except so far as indirectly it may become involved in the reactions which eliminate the calcium carbonate. It would appear obvious, however, from the fact that its ratio is reduced from about 20 per cent. in the land waters to about 3.6 per cent. in the sea waters that it suffers much secular loss. The reduction of the calcium carbonate from about 50 per cent. in the land waters to about one third of 1 per cent. in the sea waters is a fact of prime importance.

The amplest and most familiar geological observation shows that the elimination takes place mainly as normal carbonate of lime in the form of shells and skeletal parts of various marine animals, and of some plants. The gross fact of observation is the disappearance of great quantities of calcium bicarbonate from the water, and its reappearance as the secretions of animals and plants in the form of normal carbonate. Whatever may be the specific steps involved in their life economies, it seems essentially immaterial to consider here whether the animals and plants take their lime directly from the calcium carbonate, and set its surplus carbonic acid free, or whether they take it from calcium sulphate, and by using carbonic acid, derived ultimately from the waters also, convert it into carbonate, setting free the sulphuric acid to attack in turn the calcium carbonate of the sea, and thus by circuitous process free its carbonic acid, or whether the procedure follows any other indirect course; for the final result, when balanced all around, seems to be essentially the same. It may even trench on the organic cycle without essentially changing the final result. The important thing to be observed is that the process is dependent upon sea life, and varies with its

activity. There is no free supply of any competent discharging agency independent of sea life.

Variations of lime-secretion by sea life.—The amount of lime-secreting sea life is greatly influenced by the temperature of the sea and by favorable habitat. Lime-secreting sea life, both plant and animal, is greatly favored by high temperature and reduced by low. In support of this the following statements from the Challenger Report[1] and other sources may be offered, in which I have italicized the significant parts:

Species of algæ which secrete carbonate of lime are abundant in the *shallow waters* of the ocean. In the *tropical regions* especially there are massive species of *Lithothamnion, Lithophyllum, Halimeda* and other genera that make up a large part of some coral reefs and of the surrounding coral sands and muds. *Two hundred fathoms* is probably the extreme limit at which any of these organisms live in the ocean.

Rhabdospheres are especially developed in *equatorial* and *tropical regions*, and are *rarely* met with in regions where the temperature of the surface water falls below 65° F. (18.3° C.). Coccospheres, while abundant in tropical waters, are found further north and south than the Rhabdospheres; they are present even where the temperature on the surface is as *low as 45° F.*, (7.2 C.); indeed, Coccospheres attain their greatest development in *temperate regions.* These organisms are absent or *rare in coast waters* affected by rivers; they especially flourish in the pelagic currents of the open ocean. . . . In *Arctic and Antarctic waters* Coccospheres and Rhabdospheres are replaced by similar minute algæ *which do not, however, secrete rods and disks of carbonate of lime on their outer surfaces.*

Rhabdoliths and Coccoliths—the broken down parts of Rhabdospheres and Coccospheres—play a most important part in all deep-sea deposits, *with the exception of those laid down in polar and subpolar regions.*

Of all the organic remains met with in marine deposits, by far *the most frequent are the shells of Foraminifera;* it may be safely said that these organisms or their fragments are present in every average sample of marine mud, clay, ooze or sand. . . . *Nearly all the species are confined to tropical and subtropical waters; they gradually disappear from the surface-nets as the polar regions are approached,* the dwarfed forms *Globigerina pachyderma* and *Globigerina dutertrei,* being the only species met with in Arctic and Antarctic waters. . . . *In the calcareous oozes from tropical regions, the shells of all the species inhabiting the surface waters are observed in enormous abundance, but these same species are never met with in deposits from polar regions.* . . .

[1] Challenger Report, Deep Sea Deposits, pp. 257, 258–261, 263, 31 and 266.

There are not more than twenty or twenty-two species of pelagic Foraminifera, yet so numerous are the individuals of the species that they usually make up over 90 per cent. of the carbonate of lime present in the calcareous oozes of the abysmal regions of the ocean. . . .

The bottom-loving Foraminifera—those belonging to the Benthos—*are more abundant in the shallow water*, than in the deep-sea deposits, and occasionally a single species may occur in such abundance in shallow depths in some regions as to make up the greater part of a deposit. . . .

The presence of large numbers of Pteropod and Heteropod shells indicates tropical or subtropical regions, and relatively shallow depths. Abundance of the shells of pelagic Forminifera indicates the same regions, but when found without the shells of pelagic mollusks they indicate a greater depth than when these latter are present. . . . . The presence or absence, and the size of Rhabdoliths, Coccoliths and Coccospheres *give important indications as to latitude and depth*—the first predominating in tropical regions, the two latter being better developed in temperate regions, and *all disappear from the deposits as the polar waters are approached.*

A large number of these pelagic mollusks (Pteropod and Heteropod) *secrete carbonate of lime shells, and this is especially the case in tropical waters.* In *polar* regions the place of the shelled species is taken, with the exception of one or two small species of Limacina, by a *shell-less species.* The shells of the tropical species make up a large part of some tropical and subtropical deposits from moderate depths, in which there is a relatively small quantity of land débris. *Like the pelagic Foraminifera these pelagic* Mollusca attain their greatest development in the warm oceanic currents, *and diminish both in the number of species and the size and mass of the shells as the colder currents of the polar regions are approached.*

Reef-forming corals are confined to waters which, through even the coldest month, have *a mean temperature not below 68° F.* Under the equator the surface waters in the hotter part of the ocean have the temperature of 85° F. in the Pacific, and 83° F. in the Atlantic. The range from 68° to 85° is, therefore, not too great for reef-making species.[1]

An isothermal line crossing the ocean where this winter temperature of the sea is experienced, one north of the equator, and another south, bending in its course toward or from the equator, wherever the marine currents change its position, will include all the growing reefs of the world; and the area of waters may be properly called the *coral-reef seas.* . . .

Over the sea thus limited coral reefs grow luxuriantly, yet in greatest profusion and widest variety through its hottest portions.[1]

I have found no specific statements relative to the dependence of common mollusks on temperature, but the enumeration of the

[1] DANA: Corals and Coralline Islands, p. 83.

species in different latitudes clearly indicates that they are less abundant in the arctic provinces than in the tropical, from which it may perhaps be safely inferred that the lime-secreting function of the mollusks is increased by warm temperature.

In the foregoing quotations references are made to the preference of certain forms for shallow waters. The great preponderance of lime-secreting species on the shoal areas — 100 fathoms or less — is too familiar to need emphasis.

In other articles[1] I have endeavored to show that there were certain stages in the earth's history when the seas were extended widely over the continental platforms, affording conditions extremely favorable to the multiplication of lime-secreting shallow-water life. I endeavored to connect these, on an observational basis, with the great limestone-producing epochs of geological history and to show that these were correlated with genial climates over high and low latitudes alike. On the other hand, I endeavored to show that there were other periods during which the land area was increased and the sea restricted, resulting in a great reduction of this normal habitat of the chief lime-secreting forms of life. I endeavored to show that so far as the lime-secreting life is concerned, the freeing of carbonic acid was promoted during periods of extended seas and that it was retarded during periods of extended land. This holds good when considered simply from the standpoint of available area, but it becomes still more true if, as this hypothesis maintains, the extension of sea-area was correlated with favorable temperature, while the restriction of sea-area was correlated with adverse temperature. The only pelagic life that enters much into the problem is that which occupied the superficial waters of the open ocean. The area of this increased and diminished concurrently with the extension and contraction of the sea.

[1] A Systematic Source of Evolution of Provincial Faunas, JOUR. GEOL., Vol. VI, No. 6, pp. 597–608.

The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, JOUR. GEOL., Vol. VI, No. 6, pp. 609–621.

THE FORMATION OF ORGANIC COMPOUNDS AS AN AGENCY OF ENRICHMENT AND DEPLETION

The familiar fact that plants produce complex carbon compounds at the expense of the carbonic acid of the air, and that animals, aided by plants, by combustion, and by decay, decompose these compounds, and return a portion to the air as carbonic acid need not be dwelt upon. These reciprocal processes constitute a cycle which, in so far as it is mutually compensatory, affects the constitution of the atmosphere only in temporarily locking up carbon in the transient organic matter. The cycle, however, is not complete at any time, and has fallen far short of being complete at certain times. A portion of the carbon compounds are not reconverted into carbonic acid, and this residuum has been sealed up in the strata, and represents so much of depletion of the atmosphere. When this residuum was large there was a hastening of the process of robbing the atmosphere. When it was small it put less tax upon the agencies of supply. In its concrete application, the hypothesis recognizes one notable period of residual accumulation, the Coal Measures. Subordinately it recognizes others, as the Huronian and the late Cretaceous. Perhaps the Coal Measure period is the only one in which the excess of carbon composition over decomposition was so great as to seriously influence the constitution of the atmosphere, considered by itself alone, though this is open to question. A computation of the carbonic acid locked up in coal and similar carbonaceous deposits compared with that locked up in the limestones shows that the former is greatly inferior to the latter, from which it is inferred that the organic factor has been much the less influential in producing variations of atmospheric constitution, *per se*, than through its relations to the carbonates.

Respecting the organic cycle itself, it is obvious that when the sum total of vegetable and animal life increases, the amount of carbonic acid locked up in the living organisms is increased, and *vice versa*. The total mass of all the vegetable and animal living matter on the earth is some small fraction of the total

amount of free carbon dioxide. It does not seem possible now to arrive at any closely approximate estimate of this ratio. Johnson[1] expresses the belief that the growth of plants would exhaust the carbonic acid of the atmosphere in 100 years if there was no return. The average length of time during which plant products remain as living tissue is probably greater than one year, and much less than ten years, which would make the total amount of the carbonic acid so locked up a quite small per cent. of that in the air. The amount of carbon locked up in the tissue of marine life which probably was not embraced in Johnson's estimate, would somewhat notably increase the figure, but if oceanic life is considered, the free carbonic acid of the ocean must be considered also which would greatly reduce the ratio.

A study of the life of the geological periods seems to indicate that there were very notable fluctuations in the total mass of living matter. To be sure there was a reciprocal relation between the life of the land and that of the sea, so that when the latter was extended upon the continental platforms and greatly augmented, the former was contracted, but notwithstanding this it seems clear that the sum of life activity fluctuated notably during the ages. It is believed that on the whole it was greatest at the periods of sea extension and mild climates, and least at the times of disruption and climatic intensification. This factor then acted antithetically to the carbonic acid freeing previously noted, and, so far as it went, tended to offset its effects.

THE FUNCTION OF THE OCEAN AS AN ABSORBENT OF CARBON DIOXIDE

The atmosphere penetrates the ocean by simple diffusion according to the laws of gas diffusion, modified slightly by hydrostatic pressure, and this must be considered in close computations, but is too small a factor to seriously affect the larger issues.

[1] How Plants Feed, p. 47.

Absorption of carbonic acid.—Independently of this the ocean has a specific power of absorbing carbonic acid. It is important to note that this power of absorption is greatly affected by temperature, as shown by the following table of the variations for *pure* water:[1]

1	volume of	water at	0°	dissolves	1.7967	volumes of	carbon	dioxide.			
1	"	"	"	5°	"	1.4497	"	"	"	"	
1	"	"	"	10°	"	1.1847	"	"	"	"	
1	"	"	"	15°	"	1.0020	"	"	"	"	
1	"	"	"	20°	"	0.9014	"	"	"	"	

The precise rates of absorption for sea water are not accurately determined, and, indeed, are determinable with difficulty because, experimentally, they are complicated with the "loose" carbonic acid of the bicarbonates which is liable to be constantly freed by dissociation. The rates appear to be something less than those that obtain in pure water. Mr. Tolman has discussed this factor in his paper already referred to.

Release of absorbed carbonic acid.—Theoretically both the carbon dioxide diffused through the ocean and that dissolved in it should be in equilibrium with that of the air. Its quantity is dependent upon the temperature of the ocean and upon the partial pressure of the carbon dioxide of the air. Whenever the temperature of the ocean is raised a portion of its dissolved carbon dioxide is given forth. Whenever the partial pressure of the carbon dioxide of the air is reduced a portion of the free carbon dioxide in the ocean diffuses forth to reëstablish the equilibrium. The tendency to equilibrium is always present, though the constant variations of temperature and partial pressure prevent its complete realization at any particular time. If there were no counteracting influence the free carbon dioxide of the ocean would act as though it were a part of the air, and as the carbonic acid of the latter was consumed, that of the former would come forth into it.

But with loss of atmospheric carbon dioxide there is a reduction of temperature, and this increases the absorptive power of

[1] Treatise on Chemistry, Vol. I. ROSCOE and SCHORLEMMER, p. 724.

the ocean, which then tends to prevent the escape of the carbonic acid. Low temperature is, therefore, antagonistic to atmospheric resupply. Mr. Tolman has attempted to ascertain the relative value of increased absorptive power and reduced partial pressure, and, though the data are insufficient for final conclusions, finds them about equal. The withdrawal of carbon dioxide from the air does not therefore call forth a proportionate amount of free carbonic acid from the sea. Indeed, it calls forth so little that the rate of atmospheric depletion is probably not appreciably retarded by it.

Summation.—Before proceeding to make special application of the hypothesis to the recognized glacial periods it may be serviceable to bring together into briefer statement the fluctuating features of atmospheric gain and loss.

1. Of the agencies of original or permanent supply, the internal group have probably fluctuated in some rude proportion to the disruption of the crust of the earth; the external group are beyond tangible treatment, but for aught that appears may be regarded as essentially uniform.

2. Of the agencies of permanent depletion, the conversion of silicates into carbonates (the chief factor) is assumed to have fluctuated essentially with the extension and restriction of the land; the formation of carbonaceous deposits fluctuated with the well-known conditions that presided over coal accumulation.

The agencies of permanent supply and of permanent loss are both regarded as rather slow in action and as being on the whole mutually compensatory, and indeed as being in some degree self-regulative since increase of supply naturally increases consumption and reduction of supply ultimately reduces the consumption; but these relations are believed to be subject to sufficient fluctuation to give a basis for pronounced climatic changes.

The sources of temporary supply and waste are much more rapid in action and apparently more intense and voluminous in results within any brief period.

1. The sources of temporary loss are: (*a*) the locking up of carbon dioxide in bicarbonates while in solution as their second

equivalent (the great factor); (*b*) the absorption of carbon dioxide in sea water; and (*c*) its consumption in forming organic matter.

The first and greatest of these is definitely connected with extension and elevation of the land, and the second is largely a sequel to it, dependent upon the temperatures it induces, while the third does not usually coöperate with these two, but rather, to the extent of its limited competency, offsets them.

2. The sources of temporary enrichment embrace: (*a*) the discharge of the second equivalent of carbon dioxide in the sea by life action (the great factor), and (*b*) by dissociation; (*c*) the diffusion into the air of carbonic acid absorbed in the sea water due to higher temperature antagonized by reduced partial pressure, and (*d*) the freeing of carbonic acid both in the air and the ocean by the decomposition of organic matter.

These sources of fluctuation are definitely correlated with the elevation and extension of the land, on the one hand, and the extension of the sea and the reduction of the land, on the other. During an extensive elevation of the land, silicates are converted into carbonates at an increased rate and the limestones and dolomites are dissolved and carried to the sea more rapidly, both processes involving an acceleration of the consumption of carbon dioxide. Correlated with this extension of the land is a reduction of the sea area attended especially by a lessening of the area of the continental shelves which are the habitat of the chief lime-secreting life, while the area available for pelagic surface life is also lessened. Reduction in the lime-secreting life retards the incidental process of freeing carbonic acid and returning it to the atmosphere. The result is a reduction of temperature which in turn increases the ability of the ocean to absorb carbon dioxide and reduces the dissociation of the second equivalent of carbon dioxide, thus further reducing the returning process and increasing the capacity of the ocean to hold carbon dioxide notwithstanding the reduction of the partial pressure in the atmosphere. The reciprocating processes are thus temporarily affected in opposite directions so as to conjoin their results.

In periods of sea extension and of land reduction (base-level periods in particular), the habitat of shallow water lime-secreting life is concurrently extended, giving to the agencies that set carbon dioxide free accelerated activity, which is further aided by the consequent rising temperature which reduces the absorptive power of the ocean and increases dissociation. At the same time, the area of the land being diminished, a low consumption of carbon dioxide both in original decomposition of the silicates and in the solution of the limestones and dolomites obtains. Thus the reciprocating agencies again conjoin, but now to increase the carbon dioxide of the air.

These are the great and essential factors. They are modified by several subordinate agencies already mentioned, but the quantitative effect of these is thought to be quite insufficient to prevent very notable fluctuations in the atmospheric constitution. As a result, it is postulated that geological history has been accentuated by an alternation of climatic episodes embracing, on the one hand, periods of mild, equable, moist climate nearly uniform for the whole globe; and on the other, periods when there were extremes of aridity and precipitation, and of heat and cold; these last denoted by deposits of salt and gypsum, of subaërial conglomerates, of red sandstones and shales, of arkose deposits, and occasionally by glaciation in low latitudes.

T. C. CHAMBERLIN.

[The continuation of this article in the next number will embrace a discussion of the application of the hypothesis to known glacial periods, and to the oscillations from glacial to interglacial epochs, together with the agencies of localization, and a suggestion regarding the superposed minor oscillations.]

THE CARBON DIOXIDE OF THE OCEAN AND ITS RELATIONS TO THE CARBON DIOXIDE OF THE ATMOSPHERE.[1]

OUTLINE.

1. Introduction.
2. Laws of dilute solutions
   1. Mass action.
   2. Dissociation.
   3. Heterogeneous equilibrium and the change in the solubility of one salt due to the presence of others.
   4. Hydrolitic dissociation.
3. Solution of gases in pure water.
   1. Class I.
   2. Class II. — Physical solubility.
   3. Carbonic acid. — Chemical solubility.
   4. Amount of gases dissolved.
4. Solution of gases in salt solutions.
   1. Class 1. Oxygen, Nitrogen, etc.
   2. Carbonic acid.
5. The ocean salts.
   1. Amounts.
   2. Degree of dissociation.
6. The ocean gases.
   1. Oxygen, nitrogen and argon.
   2. Carbon dioxide.
      1. Simple Solution.
      2. As H_2CO_3.
      3. Modified by the ocean salts.
      4. Maximum amount held thus in the ocean under the laws of gas absorption.
      5. Ditto. As second equivalent of bicarbonate.
7. Relation of the atmospheric and oceanic CO_2.
   1. CO_2 of the bicarbonates.
   2. Dissociation of the bicarbonates.
   3. Degree of dissociation as a function of temperature and pressure.

[1] Especial thanks are due to Dr. Chamberlin, Dr. Stieglitz and Dr. Lengfeld, of the University of Chicago, for careful revision of this article and many valuable suggestions.

4. Effect of variation of pressure and temperature postulated by Dr. Arrhenius. (*a*) Upon bicarbonate in the waters of the temperate zone. (*b*) Upon bicarbonates in equatorial waters. (*c*) Upon bicarbonates in colder waters.
5. Changes in volume of the belts due to cold water advancing southward.
6. Conclusions.

THIS subject has come to have special importance on account of the investigations of Professor Arrhenius[1] and Dr. Chamberlin,[2] on the effects of the atmospheric CO_2 upon the climate of the earth. Some of the earlier important contributions on the subject are as follows:

Tyndall calculated from his experiments that the absorption of radiant heat by atmospheric CO_2 is eighty times that of the oxygen or nitrogen, and that water vapor has an absorbing capacity of ninety-two times that of oxygen or nitrogen.[3]

By repeating and extending Tyndall's experiments, Dr. Lecher and his colleague, Pretner, concluded that carbon dioxide is the only agent in absorbing the sun's heat, and maintaining the earth's temperature above that of space.[4]

Mr. J. S. Keeler criticised the above and stated that the heat is absorbed by carbon dioxide and some other agent; either water vapor or matter in suspension.[5]

Professor Röntgen showed that water vapor has a marked absorption band in the ultra red and, therefore, plays an important part in maintaining the present surface temperature of the earth.[6]

Paschen demonstrated that both these gases play important parts in the atmosphere's heat absorption, and that sometimes one, and sometimes the other is the predominant factor.[7]

[1] Phil. Mag., Vol. XLI, pp. 237–279.

[2] JOUR. GEOL., Vol. V, 1897, pp. 663–683. Also this No., pp. 545–584.

[3] Introduction of Chemical and Geological Essays, T. S. HUNT.

[4] Sitzungsberichte des Akad. der Wissenschaften d. Wien (2) Vol. LXXXII, p. 851 (2) Vol. LXXXVI, p. 52.

[5] Am. Jour. Sci. (3) Vol. XXVIII, p. 190.

[6] Poggendorf's Annalen (2) Vol. XXIII, p. 1259.

[7] Phil Mag., S. 5, Vol. XLI, No. 251, April 1896, p. 239.

The discovery that this constituent of the atmosphere is an important dynamic factor among geological agencies has led us to investigate the eighteen potential atmospheres of carbon dioxide in the ocean. This at once leads us to a consideration of the chemistry of the ocean, and here we find that the indefiniteness of our notions upon this subject is not so much due to lack of data, for that has been collected by individuals and by well equipped expeditions, as to erroneous conceptions of the relations and reactions that obtain between the several constituents of a mixed solution. Important investigations involving large outlays of time and money have been rendered nearly valueless, because they were based upon assumptions which were accepted without proof, and which are now known to be false. The importance of the first principles which govern solution and precipitation in such a solvent as water (and which have but recently been formulated) justify a review of some of them as an aid to the interpretation of the reactions taking place in that great laboratory the ocean.[1]

Mass action.[2]—It will be remembered that Berthollet in 1803 was the first to conceive of chemical reactions as governed by equilibrium, dependent both on the mass and the affinity of the constituents. The value of his discovery was not realized because he unfortunately did not believe chemical compounds to have definite compositions.

In 1864 Goldberg and Waage re-stated the law of mass action, which may be developed as follows. Let us consider any two substances, A and B uniting to form two other substances C and D.[3]

All simple reactions that have been carefully studied have been shown to be reversible, therefore, as soon as any of C and

[1] Complete discussion of the laws of dilute solution, etc., may be found in any of the up-to-date text-books on physical chemistry.

[2] W. NERNST: Theo. Chem., pp. 353-455, etc., 117-150. OSTWALD'S Outlines of Chemistry.

[3] GOLDBERG and WAAGE: Videnskabernes Selskabs Forhandlinger, 1864.

D is formed there will be a union of C and D to form A and B. This reversible reaction is expressed thus:[1]

$$A + B \rightleftarrows C + D.$$

Let the degrees of concentration of the active masses, *i. e.*, the masses in units volume of A, B, C and D be respectively p, q, p' and q'. The unit measure of concentration is the gr. equiv. per liter. Let K be the rate of combination of unit masses of A and B, and K′ that of C and D. Now the magnitude of the reaction of A upon B is evidently $K\,p\,q$ (for the number of impacts of A upon B depends directly on their concentration) and that of C and D is $K'\,p'\,q'$. Now when equilibrium is established, the reaction of A upon B = the reaction of C upon D or $K\,p\,q = K'\,p'\,q'$ (the law of mass action).

Dissociation.— From the study of electrolysis[2] of salts, Clausius was compelled to assume that at least a small portion of the salt was dissociated into its positive and negative ions, Na Cl, for instance, into the positive ion $(\overset{+}{\mathrm{Na}})$ and the negative ion $(\overline{\mathrm{Cl}})$.

Arrhenius[3] found that the osmotic pressure of a dilute solution of a salt in water, is that which it should have if a large proportion of the molecules of the salt are split into two smaller molecules (Na Cl for instance, into Na and Cl) and also that this change in osmotic pressure is a function of the electric conductivity. He was therefore compelled to conclude that practically all of the salt may be dissociated in very dilute solutions, but, in more concentrated solutions the proportion dissociated becomes smaller. It then became evident that this action is reversible and is expressed

$$\overset{+}{\mathrm{Na}} + \overline{\mathrm{Cl}} \rightleftarrows \mathrm{Na\,Cl}.$$

[1] A simple illustration of a reversible reaction is the evaporation of water in an enclosed dish. Particles of water leave the liquid to form the superincumbent layer of water gas. As soon as any of the gas is formed it in turn gives back water particles to the liquid. Equilibrium is established and there is apparently no farther evaporation when the number of particles given off by the liquid equals the number of particles returned by the gas.

[2] Ges. Abh. (sep. papers) II, 135, 1867.

[3] ZEITS: Phys. Chem., Vol. I, pp. 631 ff.

Then, according to the law of mass action—

$$K_1 ab = K_2 c$$

where a and b are the concentrations of the ions ($\overset{+}{Na}$ and $\overline{Cl}$) and c of the dissociated salt.[1]

$$\frac{ab}{c} = \frac{K_2}{K_1} = K . \qquad (2)$$

This K is called the ionization or dissociation constant, and is a constant under constant temperature and pressure, but is different for each different salt.

Salts, strong acids and bases (hydrochloric acid, sodic hydrate, etc.) are the substances most dissociated, while the weaker acids and bases (acetic acid, ferric or ammonium hydrate, etc.) are dissociated to a less degree, *i. e.*, the constant K is smaller.

It follows directly from equation (2) that the more diluted the solution the more complete is the dissociation. If the strength of the solution is such that concentration a and b are each represented by 2 and c by 4; and then the concentration of all be decreased so that a and b become 1, we find by substitution in the equation (2) that c also must become 1, and the ratio of dissociated to undissociated or *molecular* salt, is 1 : 1 instead of 1 : 2.

Heterogeneous equilibrium.—We may have some undissolved substance (C) in contact with a saturated *molecular* solution (C_1) of the same substance which is dissociated, more or less, into its ions (A and B). The concentrations are a and b for the ions, c for the undissolved (solid) salt, and c_1 for the undissociated dissolved part of C. Equilibrium being established between the solid C and the molecular solution of the solid ($C \rightleftharpoons C_1$), the equation is

$$\frac{c}{c_1} = K_1 . \qquad (3)$$

But the concentration of a solid at given temperatures and pressures is a constant (its specific gravity) ($c = K_2$), therefore

[1] This simple formula is not strictly accurate in the case of electrolytic dissociation but is correct enough for our purpose.

$$c_1 = \frac{K_2}{K_1} = K_3 . \qquad (4)$$

Now the dissolved undissociated part of the salt dissociates into its ions

$$(C_1 \rightleftarrows A + B) \quad \text{or} \quad \frac{ab}{c_1} = K_4 \qquad (5)$$

but substituting from (4)

$$ab = K_3 K_4 = K. \qquad (6)$$

This K is called the constant of solubility, or the ion product. This is the law governing precipitation of electrolytes, and under it there are three cases.

(a) $ab > K$.
(b) $ab = K$.
(c) $ab < K$.

(a) If ab is greater than K the action goes $A + B \longrightarrow C_1$, and again $C_1 \longrightarrow C$, therefore we have precipitation.

(b) If $ab = K$, we have equilibrium, and neither precipitation nor solution takes place.

(c) If ab is less than K the action goes

$$C_1 \longrightarrow A + B \text{ and } C \longrightarrow C_1 ,$$

that is solution takes place.

Now, if we mix solutions of two or more salts, besides the undissociated salts which were present in the separate solutions in equilibrium with their respective dissociated ions, we will have in the mixture also the salts that can be formed by the union of the positive ion of each salt with the negative ion of each of the other salts. From the foregoing the following propositions are derived:

Proposition 1.—Mixed solutions of two or more salts will contain all the salts that can be made by the combination of the ions of the original salts together with the free ions.

Proposition 2.—Of all these salts that one will be precipitated first whose product of ionic concentration first exceeds its constant of solubility or ion product.

If a salt be added to a mixture of salts in solution, there is added not only the salt itself but its ions also. If one of the

salts of the original mixture have an ion in common with the new salt (as for instance Cl in Na Cl and KCl), then the product of the ionic concentration of each salt is increased. Now if, before mixing, this product for either salt nearly equaled its constant of solubility, the increase may be enough to bring about precipitation. If, for instance, to a solution of lead chloride, which is not altogether insoluble in water, is added a sufficiency of K Cl, this addition causes a precipitate of lead chloride, since the addition of the Cl ions of the potassium chloride causes the product $Pb \times Cl^2$ to be larger than K where Pb = concentration of lead ions, and Cl = concentration of chlorine ions.

If, however, the salt added has no ion in common with ions of the other salts, it will take away from the ions of all the salts to form some of all the undissociated salts that result from the combination of the two new ions with all the ions of the original salts, therefore the product of ionic concentration for all the salts is decreased, or, in other words, the solubilities of all the salts are increased. Hence,

Proposition 3.—In a mixture of salts those with a common ion increase the ionic concentration of each, aiding precipitation, and those without a common ion decrease ionic concentration of each, and retard precipitation, each increasing the solubility of the other.

Hydrolytic dissociation.—Water, which is one of the weakest of acids, is itself dissociated into hydrogen and hydroxyl ions ($H_2O \rightleftharpoons H + OH$); but this takes place to a very slight extent only. Kohlrausch found that at 18° C. for water distilled in a vacuum there is less than one gram of hydrogen ions in two million liters of water,[1] and Ostwald, Arrhenius, and Weis, and Kohlrausch[2] in later experiments (see reference below), found about one-sixth of this dissociation by other methods. Of course these free ions will react with ions of the salts in

[1] W. NERNST: Theo. Chem., pp. 658–662.

[2] F. KOHLRAUSCH and AD. KEYDWEILLER, Zeits. f. Phys. Chem., XIV, pp. 317–330.

solution to form some undissociated acid and base ($Na\,Cl + HOH \rightleftharpoons NaOH + H\,Cl$). But since there is such a very small amount of free dissociated ions of water and the dissociation constants of sodic and hydrochloric acid are large, this action is very slight. However, the salts of the weakest acids and bases are affected more by the same amount of dissociated water than those of the stronger ones, because, as shown by equation (2), K is smaller, therefore a larger amount of the undissociated acid, or base, exists in proportion to the ions.

Water when heated becomes more dissociated, and therefore a stronger acid, and this fact is sometimes made use of in the analytical laboratory, and is an important factor determining the composition of minerals deposited from hot solutions.

Solutions of gases in pure water.—If a gas dissolves in a substance with which it is perfectly neutral, that is, if no chemical reaction takes place between the gas and the solvent, then the amount of the gas dissolved in the liquid at a given temperature varies directly with the gaseous pressure, or partial pressure, if there be more than one gas.

Now, if any gas were absolutely neutral to the solvent, and if on solution its molecule suffered no change in constitution, we should get the same amount of heat absorbed or given off in the solution that would be absorbed or radiated by the same amount of gas brought to the density of the dissolved gas.

But upon solution in water it is found that some gases suffer a larger heat change than can be explained by any mere physical change in volume, while others have the same or nearly the same change in temperature, as that calculated upon the assumption of simple physical absorption. It has been shown that the gases with this large heat change upon solution undergo besides physical diffusion, a chemical change, more or less extensive. Therefore, gases may be arranged in two classes. The first class is composed of those gases which have but a slight reaction with water, and are sparingly soluble in that menstruum, and the other, of those which have large coefficients of solubility and which react with water to form definite compounds.

Of the former, those found in the ocean are nitrogen, oxygen, argon, etc., and of the latter, none are found in appreciable quantities, but we may take ammonia as a good example. This last unites with water to form NH_4OH which compound is known to exist as such.[1] The behavior of carbon dioxide towards water places it between these two classes. It unites with water to form H_2CO_3. This acid has never been separated as such, but doubtless exists.[2] This action does not give such a large coefficient of solubility as is characteristic of the gases of the second class.

The solution, then, of oxygen, hydrogen and argon, etc., is simple diffusion due to the attraction between the molecules of the solvent and those of the gas, while the solution of CO_2 in pure water includes (1) a diffusion of the gas molecules between water molecules and (2) a chemical reaction between the gas and water molecules to form carbonic acid.

Bunsen[3] has determined the solubility of the carbon dioxide for different temperatures as follows:

Solubility of CO_2 in H_2O, 1 vol. H_2O at t degrees and 760 mm. pressure dissolves V vols. CO_2 gas reduced to 0° C. and 760 mm pressure.

t° C.	V.	t° C.	V.	t° C.	V.
0	1.7967	7	1.3339	14	1.0321
1	1.7207	8	1.2809	15	1.0020
2	1.6481	9	1.2311	16	0.9753
3	1.5787	10	1.1847	17	0.9519
4	1.5126	11	1.1416	18	0.9318
5	1.4497	12	1.1018	19	0.9150
6	1.3901	13	1.0653	20	0.9014

In the above table the solubility is determined for pure CO_2 unmixed with other gases under 760 mm pressure. For low pressures the solution of the gas is proportional to the pressure or the partial pressure of the CO_2.

[1] PROFESSOR MALLET, Am. Chem. Jour., Vol. XIX, pp. 804–809.

[2] DAMMER, Anorg. Chem. II, 1, p. 871.

[3] BUNSEN'S Gasometry, pp. 287, 128, 152.

The atmosphere, of course, is not pure CO_2, but a mixture of gases in the following proportions: Oxygen, 20.9 vol.; nitrogen, 79.1 vol., of which 01.18 per cent. belongs to that group of gases called argon,[1] CO_2 .03 vol.

At any given temperature the amount of the atmospheric gas dissolved in pure water is the product of the amount dissolved under 760 mm pressure of the pure gas by the partial pressure of gas in the air. This holds for the carbon dioxide in spite of the chemical reaction $CO_2 + H_2O \rightleftharpoons H_2CO_3$. This may be seen as follows:

Let a, b, and c be the concentrations respectively of CO_2, H_2O, and H_2CO_3, therefore

$$\frac{ab}{c} = K_1,$$

but the water is so greatly in excess that its concentration, b, can be considered as a constant (K_2) or

$$\frac{a}{c} = \frac{K_1}{K_2} = K.$$

Therefore the amount H_2CO_3 $[c]$ varies directly with the amount CO_2 $[a]$ dissolved, and this is proportional to the partial pressure of the gas. Making the calculations from Dittmar's tables, we find that one liter of pure water at 15° C. dissolved from the atmosphere .32cc of CO_2, 7.2cc of oxygen, and 13.2cc of argon and nitrogen.[2]

The absorption of gases in salt solutions.—The researches of J. Setchenow[3] show us that a gas dissolved in salt solution obeys the same laws as if the salt were not present, if there is no chemical reaction between the gas, the salt, and the solvent. In this case, however, the attractive power between the molecules of the solvent and the gas is partially satisfied by the salt mole-

[1] Chem. News, 72 p. 308. Comptes Rendus de l'Academie des Sciences, CXXI, p. 605.

[2] Challenger Reports, Vol. I, pp. 167-168.

[3] Ann. de Chemie: pp. 226-270.

cules. From some of his tables we find that for a solution of the strength of the oceanic brine the diminution of the solubility for gases of this class is somewhere near 20 per cent. (*loc. cit.* pp. 245-259).

If, however, there is a chemical reaction between the gas and the salt, the solubility is increased by so much. Oxygen, nitrogen, and argon do not react with the salts of the ocean, but CO_2 does. The carbonic acid dissociates into its ions, and these ions react with the ions of the salts to form small quantities of undissociated compounds. This reaction has an appreciable effect only where the original salt is formed from weak acids and bases. From Mr. Setchenow's tables[1] for Na Cl solution of the strength of the sea water we gather that this increase for CO_2 would not be over 20 per cent. of that dissolved by pure water (.3^{cc} per liter, a quantity wholly negligible).

The ocean salts.[2]—The average temperature of the surface of the ocean is about 15° C.

The proportion of the different salts in the ocean, Professor Dittmar finds to be wonderfully constant for all parts of the sea water. He gives the following analysis for the salt:

Cl	55.292%
Br	.1884
SO_3	6.410
CO_2	.152
CaO	1.676
MgO	6.200
K_2O	1.332
Na_2O	41.234
Basic O (equivalent to Hologen)	—12.493
	100

This table we have recalculated for the percentages of the ions according to modern usage, and in order to facilitate subsequent discussion, as follows:

[1] Loc. cit., p. 246.

[2] Phys. Chem. Chall. Exp., Vol. I. Narrative of the Cruise of H. M. S. Challenger, 1885; Ency. Brit. XXI, pp. 611 to 614.

(Cl)	55.292%
(Br)	.188
(SO_4)	7.692
(CO_3)	.207
(Na)	30.593
(K)	1.105
(Mg)	3.725
(Ca)	1.197
	99.999

While the average constitution of the salts remains a constant, the salinity of the ocean is variable. Averaging 327 analyses, it is found that the average amount of salt is 34.7 grams per kilogram sea water, or taking the average specific gravity of the ocean as 1.026, about 35.6 grams per liter.

Applying this to the second table, we find that the total number of grams of the different ions per liter is as follows:

(Cl)	19.68
(Br)	0.07
(SO_4)	2.74
(CO_3)	0.08
(Na)	10.89
(K)	0.4
(Mg)	1.33
(Ca)	0.43
	35.69

Dividing by the equivalent weights, we find the relative strength of the ions per liter to be as follows, where the normal solution (one which contains as many grams per liter as the equivalent weight of the substance) is taken as unity.

Relative strength per liter	
(Cl)	0.55 N. sol.
(Br)	0.0009 "
(SO_4)	0.057 "
(CO_3	0.0027 "
(Na)	0.47 "
(K)	0.01 "
(Mg)	0.112 "
(Ca)	0.022 "

Dividing the relative strength of the bivelant ions by 2, we find the relative number of ions.

Relative No. of ions	
(Cl)	5500
(Br)	9
(SO_4)	285
(CO_3)	13
(Na)	4700
(K)	100
(Mg)	560
(Ca)	110

In the light of the previous discussion, we see that there must be sixteen different salts and eight different ions in the solution, under the supposition that the salts with bivalent ions dissociate completely into their metal and acid ions, and always neglecting the subordinate elements, such as strontium, iodine, gold, etc. Since, however, in a solution as strong as the sea water, there are two reactions in the dissociation of the salts having one bivalent ion, viz.:

$$Na_2SO_4 \rightleftarrows (\overset{+}{Na}) + (\overset{+}{Na}) + (\overline{\overline{SO_4}})$$
$$Na_2SO_4 \rightleftarrows (\overset{+}{Na}) + (\overline{NaSO_4})$$

there are also these extra ions, viz., ($Na\ SO_4$), of the bivalent acids and bases. Also instead of simply the salt of the radical CO_3 (normal carbonate) we have both the bicarbonate of the acid radical ($H\ CO_3$) and the acid radical itself.

From the propositions of the theory of dilute solutions it is possible to develop equations whose solutions will give the proportions of the various undissociated salts and of the free ions, but these computations would be of little value because of their complexity, and because the ocean water is too strong a solution for a numerical application of the equations developed for dilute solutions.

However, assuming that the constant K is of the same order of value for all the salts, and that the concentration of the free ions may be expressed by the relative number of ions calculated under the assumption that the salt is completely dissociated (see table p. 596), and neglecting the presence of the bicarbonate ion, we see that the relative amount of the undissociated salts will be expressed roughly by the products of the concentration of their respective radicals, and, therefore (from table p. 597) 1) $Na\ Cl$, 2) $Mg\ Cl_2$, 3) $Na\ SO_4$ exist in molecular form in greatest quantity, the rest following in about the order:

4)	$CaCl_2$
5)	K_2Cl
6)	$MgSO_4$
7)	Na_2CO_3
8)	NaBr
9)	$CaSO_4$
10)	K_2SO_4
11)	$MgCO_3$
12)	$MgBr_2$
13)	$CaCO_3$
14)	K_2CO_2
15)	$CaBr_2$
16)	KBr

If we examine the following table of Kohlrausch for K Cl and apply it to all the salts of the ocean, comparing the strengths of the oceanic solutions with the strengths of the K Cl solutions given in the table, we can form an approximate idea of the proportions of the molecular or undissociated salts to their respective free ions.[1]

N.	Per cent. dissociated molecules
1.	.75
.5	.78
.1	.86
.01	.94
.001	.98
.0001	.99

Under N is the strength of the solution where the normal solution is taken as unity.

From the above table and the one on p. 597 we conclude that somewhere about 80 per cent. of the sodium chloride is dissociated into its ions. We cannot judge so well about the sodium sulphate or magnesium chloride, but they also have some considerable amount of molecular salt, possibly more than of the sodium chloride. The potassium chloride is somewhere around 90 per cent. dissociated, and the potassium bromide, the last of the series, is practically completely dissociated.

The ocean gases.—The gases found dissolved in the ocean

[1] NERNST: Theo. Chem., p. 314.

water are nitrogen, oxygen, argon, and carbon dioxide. The nitrogen, argon, and oxygen are absorbed into the ocean directly from the air. Since the ocean is very generally agitated into waves, we may suppose that the gases dissolved in the outer portion of the surface water are in direct equilibrium with those of the air. The surface waters are being saturated with gas at temperatures varying with the daily and seasonal changes. Therefore, if there is no depletion or increase of these gases due to chemical or organic agencies we may assume roughly that the ocean, on the average, contains these gases in a proportion which may be calculated from the coefficients of absorption for the average temperature of the surface of the sea, which we assume to be 15° C. Therefore, to find the average amount of nitrogen, argon, and oxygen dissolved in the ocean we must determine their respective coefficients of absorption for sea water. From the remarks on the effect of salts on the solution of gases we should expect that the salt water would dissolve a little less of the above-mentioned gases than fresh water, because (1) salts in solution decrease the solubility of gases, and (2) because none of the gases react chemically with the ocean salts.

The following table, which is taken from a larger table of Dittmar, shows that these theoretical conclusions are correct:

cc AIR DISSOLVED PER LITER.[1]

	Pure water	Sea water
−5°	.....	27.27
0°	29.54	23.78
5°	26.09	21.08
10°	23.37	18.92
15°	21.16	17.17
20°	19.33	15.72
25°	17.80	14.44
30°	16.49	13.44
35°	15.36	12.53
40°	14.37	.....
45°	13.50	.....
50°	12.73	.....

[1] Loc. cit., pp. 172 and 175.

Taking, therefore, the coefficient of absorption for sea water as given by Dittmar[1], we find that at 15° C. the sea water dissolves 5.83^{cc} of oxygen and 11.34^{cc} of nitrogen and argon, which is less than shown by the figures given on page 594 for the absorption of pure water. We find on comparing these figures with the average of the gases as found in the Challenger analyses that the amount of the nitrogen and argon is near the amount calculated for the temperature of the water at the time it was collected, as we might expect in view of the mixing, etc., it undergoes. The oxygen, however, is always low, as it is used up in the oxidation of the organic matter in the ocean. It is almost up to the calculated amount in the surface water but a very large deficit in the deeper water. We may suppose, then, that the above figure for nitrogen and argon is approximately correct, but that the oxygen figure is considerably too high.

It is evident that we have a very different case to deal with in the solution of the CO_2 in the ocean. We have already found three ways in which the gas is held in solution. (1) Simple physical absorption; (2) united with the water to form (H_2CO_3); (3) held by equilibrium reactions with the salt ions. The total that can be held in these three ways at atmospheric partial pressure of the gas and at the average temperature of 15° is about 0.3^{cc} of CO_2 per liter of sea water.

Now, under the assumption that the partial pressure of the CO_2 increases with the depth of the ocean; and that the rate of this increase obeys the same laws as the increase of atmospheric pressure with the depth of the atmosphere, and, taking the average depth of the ocean at the large figure of three miles, we find a formula developed by Professor Woodward[2] that the pressure at that depth is 4.4 that at sea level. Also assuming that *all* the ocean is at a temperature of 0° C. (instead of only the portion at great depths) we find as a maximum estimate the ocean cannot hold over 2.4^{cc} CO_2 per liter dissolved as a gas,

[1] Loc. cit., p. 139.

[2] Communicated in a letter to Dr. Chamberlin.

according to the laws of gas absorption; this it is to be noted, under the unrealizable conditions of a uniform temperature of 0° C. and an average depth of three miles. But Mr. Buchanan found that on boiling, sea water gives an average 45^{mg} or 23^{cc} CO_2 per liter, or ten times the greatest amount the ocean could hold as a gas under more favorable conditions than those of the present time. Mr. Jacobson found 90^{mg} upon distilling the water to dryness. Mr. Buchanan thought that this great excess of CO_2 over that which could remain in solution under atmospheric pressure of CO_2 must be held in some sort of loose combination with one of the salts, and he decided upon the sulphates as the retaining agent. Such a misinterpretation, of course, might be expected at that time from the imperfect knowledge of the nature of the solutions. Before determining the free CO_2, therefore, he precipitated the sulphate with barium chloride, and unfortunately he must have obtained a mixture of $Ba\,SO_4$ and $Ba\,CO_3$, so that his numerous determinations are all probably somewhat too small.

But in spite of this his analyses show that the ocean contains about eighteen times the CO_2 of the atmosphere. Now, bearing in mind Professor Arrhenius' statement, "that to lower the temperature of the temperate region 5°, and bring on glaciation, the CO_2 of the atmosphere needs to be diminished to from 62 per cent. to 55 per cent. of its present value,"[1] the following questions suggest themselves:

1. How is the excess of the CO_2 found in the ocean at the present time held in solution?

2. Is it in equilibrium with that of the air?

3. If so, what proportion of the ocean gas will be brought out into the air by a diminution of the partial pressure of the CO_2 to an amount from 62 per cent. to 55 per cent. of its present value?

4. How much will the consequent fall of temperature increase the ocean's capacity for CO_2?

5. What is the relation between these two?

[1] Loc. cit., pp. 237–279.

In its immediate action, the ocean certainly has a moderating effect upon the temperature of the land. The great amount of heat necessary to raise the temperature of the water one degree, together with its vast evaporating surface, distributes the warmth received during the day over the night, much of the excess of the heat of summer throughout the winter, and the great downpour of radiant energy upon the tropics over the temperate and frigid zones. The question then arises: In the greater cycles of the variation of the earth's climate (whether dependent directly or only in part upon the fluctuations of the carbon dioxide content of the atmosphere) does the ocean still play the beneficent rôle of protector against the advances of the greater winters, furnishing the atmosphere some of its enormous supply of CO_2 as a blanket against the cold? Or, does the increasing cold cause the ocean, like a selfish monster, to keep a more grasping hold on the precious gas as the need of it becomes more imperative?

1. Besides the CO_2 which may be absorbed by the ocean from the air, it receives the gas (1) from the respiration of aquatic animals (2) from the decomposition of organic matter (3) from the interior of the earth through springs, etc., and (4) from the bicarbonates brought in by the rivers.

We find from analyses of the water of the principal rivers[1] of Europe, that about 60 per cent. of the entire mineral content of the river water is calcium carbonate dissolved as calcium bicarbonate. This calcium bicarbonate then is the great source of the extra carbon dioxide of the ocean. When this bicarbonate mixes with the ocean it is no longer strictly speaking, calcium bicarbonate, but mostly bicarbonate ions in equilibrium with small amounts of sodium, magnesium, calcium and potassium bicarbonates.

2. The various bicarbonates have been subject to numerous investigations since the researches of H. Rose[2] in 1835. These contributions show that sodium, potassium, ammonium, and

[1] BISCHOF, Chemical and Physical Geology, Vol. I, pp. 76, 77.

[2] Journal für Praktische Chemie, Neue Folge 10, 1879, pp. 417–444. Zeits. für Anorg. Chemie., Vol. XVII, pp. 170–204.

magnesium bicarbonates, partially dissociate at ordinary temperatures into the normal carbonate, giving out CO_2. Treadwell and Reuter have shown in the latest and most complete research on the subject (see reference above) that when calcium carbonate is dissolved under different partial pressures of CO_2, that the proportion of calcium to carbon dioxide, indicates that practically a pure bicarbonate, and not a mixture of bicarbonate and carbonate, is present in the solution.

The difference between the sodium, magnesium, etc., bicarbonates on the one hand, and the calcium bicarbonate on the other is seen from the following: (1) For the dissociation of magnesium bicarbonate we have in a saturated solution,

$$Mg(HCO_3)_2 \rightleftharpoons MgCO_3 + H_2CO_3.$$

We have seen that the H_2CO_3 is directly in equilibrium with the CO_2 in the air; therefore at a given temperature, the degree of dissociation depends upon the partial pressure of the CO_2 in air. With variations of temperature, the colder the water, the larger is the portion of bicarbonate present, and therefore, the larger is the proportion of carbon dioxide in the ocean to that in the air. (2) For calcium bicarbonate we have:

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3 + H_2CO_3.$$

But $CaCO_3$ is very slightly soluble, and therefore practically a constant for a *saturated* solution. Therefore, we do not have a mixture of bicarbonate and appreciable quantities of the carbonate, but the salt in solution is nearly all bicarbonate, and by lessening the partial pressure of the CO_2, $CaCO_3$ is precipitated from the saturated solution and the bicarbonate decreases. However, this difference between $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ which Treadwell has emphasized, only holds for saturated solutions. It is evident that for an under-saturated solution of $Ca(HCO_3)_2$ we may have a larger proportion of normal carbonate than in the saturated solution and still no precipitation. Also, in ocean water (see p. 591), the numerous different salts tend to increase the solubility of the normal

carbonate, and allow perhaps a somewhat greater dissociation of the bicarbonate into carbonate. The bicarbonate in the ocean is, as shown above, not calcium bicarbonate, but bicarbonate of all the bases in solution, so that Treadwell and Reuter's investigations upon *pure* calcium bicarbonate in *saturated solution* cannot be taken to prove that the bicarbonates of the unsaturated sea water cannot be dissociated.

As direct evidence that the ocean is not saturated with calcium acid carbonate, we find (1) of the many hundred bottles of the Challenger's samples of sea water, from all depths and collected at all temperatures, kept several years, only one or two showed deposit of lime.[1] (2) Seashells from the bottom of the Pacific show corrosion and resolution.[2] Pteropod shells and foraminifera tests are slowly dissolved as they sink. The Pteropod shells are not found below fifteen hundred fathoms, and two thousand eight hundred fathoms is the limit for the globigerina ooze.[3] (3) Thoulet found by actual experiment that sea water will dissolve calcium carbonate from shells, corals, etc.[4] (4) Usiglio, studying the evaporation of the Mediterranean water at Cette, found that no precipitate was formed until the specific gravity of the sea water increased from 1.02, the specific gravity of the unevaporated water, to 1.0503 when the first precipitation begins, composed largely of calcium carbonate with ferric oxide.[5]

DEGREE OF BICARBONATE DISSOCIATION.

From twenty-seven analyses by Jacobson, we find an average of 91.4^{mg} per liter of free CO_2, and 120^{mg} CO_2 in the normal carbonate, or the bicarbonate is so dissociated that 25 per cent. of its second equivalent of CO_2 is lacking.[6]

[1] Loc. cit., p. 221.

[2] JOUR. GEOL., Vol. I, p. 504.

[3] Loc. cit., p. 221.

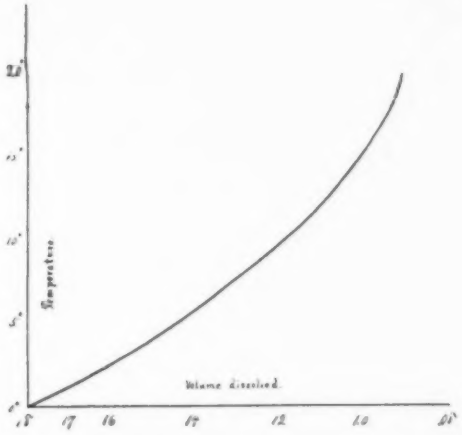
[4] Comptes Rendus, Vol. CVIII, p. 753.

[5] Encyl. Brit., Vol. XXI, p. 229.

[6] Uber die Luft des Meerwassers Ann. der Chemie und Pharm., Vol. CLXVII (1873), pp. 1–38.

From several hundred determinations of Buchanan, we strike an average of 45^{mg} free CO_2 per liter, to 53.4^{mg} CO_2 per liter of the *first* equivalent, *i. e.*, only 84 per cent. of the second equivalent is found in the ocean. Mr. Jacobson's analyses show a larger per cent. of the carbonates than were found in the Challenger's samples, which might be expected, as Jacobson's were collected only from the North Sea into which flow the great lime-bearing rivers of northwestern Europe.

To prove positively that the ocean bicarbonate dissociates into carbonate and free CO_2, Professor Ditmar shook in the air



FIGS. 1 and 2 represent respectively the effect of temperature on the solubility of CO_2 in pure water, and upon the dissociation of Na H CO_3.

FIG. 1 is taken from table on page 593 and under 760 mm pressure CO_2. The temperature is recorded on the ordinate, and on the abscissa are the volumes of CO_2 absorbed, compared with the volume of water in which it is dissolved.

a sample of sea water, that had an excess of CO_2, and found that CO_2 was given off, and that the ratio of the two equivalents was 100:84 at 13° C., exactly the same, it happens, as we found from averaging Buchanan's analysis. Therefore we may consider it as certain that the largest part of free CO_2 in the

ocean is held as the second equivalent of bicarbonate, and that this is held in equilibrium with the gas in the air.

We know then from the above that the dissociation of the bicarbonate is a function of the temperature, and also of the partial pressure of the superincumbent CO_2. The solubility of CO_2 as a gas not attached to form bicarbonate, is also a function of temperature and pressure, but that these functions are not the same, may be seen from an inspection of the

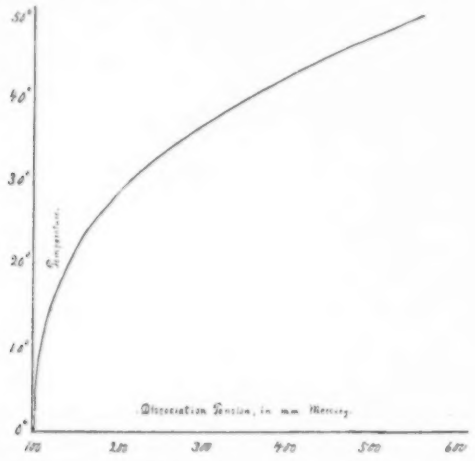


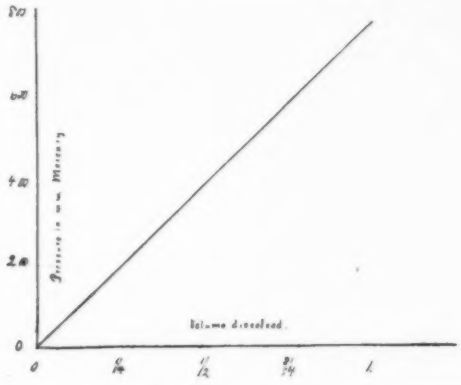
FIG. 2 is plotted from Dr. Dibbett's tables.[1] On the ordinate are the temperatures and on the abscissa the increase of the dissociation of the Na H CO_3 in mm of mercury which represents the loss of the second equivalent of CO_2 from the solution.

accompanying curves. Professor Ditmar has experimented upon the effect of changes of partial pressure and temperature upon the CO_2 in the ocean. This includes both the effect upon the portion simply dissolved and that as second equivalent of bicarbonate. We shall discuss these results under Professor Arrhenius' hypothesis of lowering the surface temperature to

[1] Ueber die Loslichkeit und die Dissociation des sauren kohlens Kaliumes, Natriurns und Ammomiums, Journal für praktische Chemie, neue Folge 10, 1879, pp. 417-444.

an average of 10° C., and the diminution of the partial pressure he has postulated as sufficient to cause this drop in temperature.

We find from Professor Ditmar's investigation (see tables and figures, pp. 609 and 610) that as the waters of the ocean become warmer, the effect of a change in the partial pressure of atmospheric CO_2 upon the bicarbonate dissociation becomes greater, while near zero a change in partial pressure has no effect on the dissociation of the bicarbonates of the ocean. On the



FIGS. 3 and 4 show the relation between the partial pressure of CO_2 and its solubility in pure water on the one hand and the solubility of $Ca\,H_2\,(CO_3)_2$ on the other.

FIG. 3 represents the simple law of gas absorption that the amount dissolved is directly proportional to the partial pressure. The pressure is plotted on the ordinates in mm of mercury and the volume of gas absorbed on the abscissa.

other hand, the effect of any postulated fall in temperature, causing the bicarbonates to take up CO_2, is the greatest at the temperature just above 0°, and becomes less for higher temperatures. So that a fall in temperature of the colder waters of the ocean is correlated with the greatest absorption of CO_2, and without the counteracting effect of decreasing partial pressure. In equatorial waters, however, the fall in temperature does not

produce so great an increase in the absorption of the CO_2, and the effect of decreasing tension of atmospheric CO_2 approaches a maximum.

These facts, therefore, naturally divide the discussion into three parts. Under Professor Arrhenius' postulates as to change in temperature and pressure, we shall discuss the relative effect of these two opposing factors in the temperate waters whose temperature is the average surface temperature of the ocean, viz., 15° C. (2) Ditto for the tropical waters whose temperature is above 15° C. (3) Ditto for the polar waters whose temperature is below this.

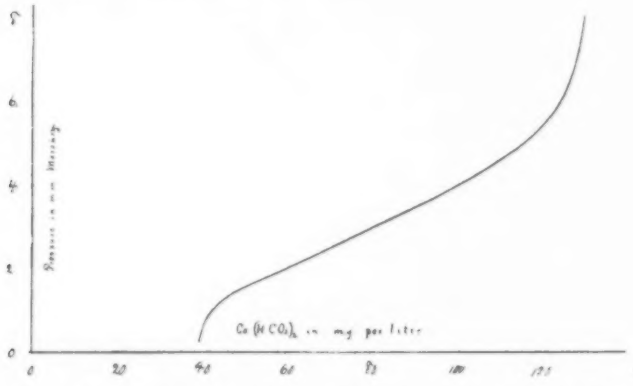


FIG. 4 is from Treadwell's and Reuter's dissertation (see reference, p. 603). The partial pressure is represented on the ordinate in mm of mercury and the amount of calcium bicarbonate dissolved in m. g. in the abscissa. At atmospheric pressure 15° C. the amount dissolved in pure water at saturation is 38.5 *m. g.* per liter, which is much less than the amount of bicarbonate in the sea, as we might expect from the previous discussion.

The only experiments which have been made upon sea water (and so under the actual conditions of the problem) are represented in Fig. 5. Professor Ditmar took a special sample of deep ocean water which was so charged with CO_2 as to have its bicarbonate fully saturated with CO_2. This he shook violently in a bottle constantly renewing the air until there was no more

loss of CO_2 from the water and no more gain in the air above the water. The carbon dioxide remaining in the water was thus determined, and the degree of the bicarbonate dissociation calculated. This was repeated for various temperatures.

The table is as follows :[1]

t	N	Pure Air (n_0)	Ordinary Air (n_1)
2	200	1.90	
2	200	2.04	
2	52		2.06
10	200	1.70	
13	50		1.84
15	100	1.63	
15	200	1.50	
20	200	1.42	
25	53	1.53	
32	52	1.33	
32	52		1.89
32	150		1.82

t=equals temperature. N=number of times air was renewed until loss of CO_2 from water ceased. n_0=ratio of first to the second equivalent of CO_2 in bicarbonate when shaken in air free from CO_2, where 2.00 represents fully saturated bicarbonate and 1.00 simply the normal carbonate. n_1=the same for ordinary air.

These experimental data do not permit the drawing of any very accurate conclusions. Professor Ditmar states that these are only preliminary, and has promised us a completion of this work, which we await with impatience. However, we must needs use what we have, and referring to curve 5, we see that at 15° the ocean will contain about 83 per cent. of the total second equivalent of CO_2, and at 10°, about 88 per cent. of it, or an increase of 5 per cent. of the second equivalent which is represented by the line *a–b* in figure. For pure air artificially freed of CO_2 at 10° the dissociation goes through 70 per cent. but Professor Arrhenius does not postulate a complete removal

[1] Enyc. Brit., Vol. XXI, p. 612.

of CO_2 from the air, but a diminution of from 62 per cent. to 55 per cent. of the present partial pressure of the gas, and this decrease in dissociation caused by the decrease of the partial

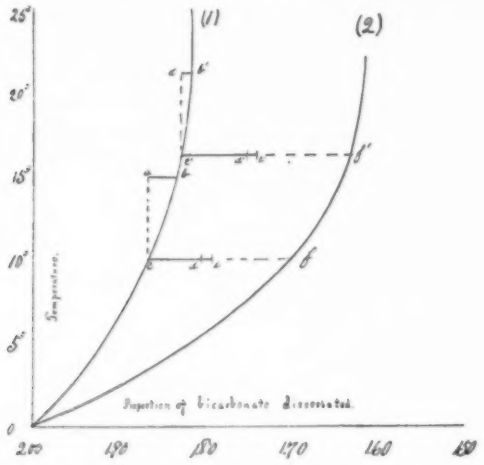


FIG. 5 is plotted from Professor Ditmar's table on page 609. The figures in the table are not very constant, but we have taken those that seem to correspond best with each other. On the ordinate are the temperatures, and on the abscissa the dissociation of the ocean bicarbonate, 2.00 representing fully saturated bicarbonate and 1.00 normal carbonate, the partial pressure of CO_2 in the curve (1) is that of the atmosphere as it is at the present time and for curve (2) there is 0 pressure of that gas. The two curves have been plotted arbitrarily to cut a 0°, but Professor Ditmar shows that there is probably no dissociation at 2° to 3° above zero.

The line *cf* connects the two curves at 10° (the temperature of the temperate regions Dr. Arrhenius postulates to develop a glacial period) and the points *d* and *e* show the bicarbonate dissociation at a partial pressure of CO_2 reduced respectively to 62 and 55 per cent. of its present value. *a b* represents the decrease of the dissociation of the bicarbonates due to fall of temperature from 15° to 10°) and *c d* and *c e* the increase of the dissociation due to a decrease of 62 per cent. and of 55 per cent. of the present value of the partial pressure of CO_2 in the air. *a' b'* and *c' d'* and *c' e'* represent the same factors for a decrease of temperature from 21° to 16° and the same decrease as postulated above in the partial pressure of the CO_2.

pressure of the gas is represented by lines *c–d* and *c–e*; so that the dissociation will be between the two, that is, viz., from 76 per cent. to 81 per cent., *i. e.*, these data show that the falling

temperature counteracts within 2 per cent. to 4 per cent. of the total CO_2 as second equivalent, the effect of the decrease in the partial pressure.

These estimates are of course founded on too small an experimental basis, and the data themselves show too great disagreements to conclude that the decrease of the dissociation due to the falling temperature, counteracts exactly within 2 per cent. to 4 per cent. of the second equivalent of CO_2, the increase due to the diminishing partial pressure ; but we may conclude *that they are probably of the same order of magnitude*, or that *a–b* is comparable in length with *c–d* or *c–e*.

All this however, is under the proposition of Professor Arrhenius, that a 5° lowering of the average climate of the *temperate* regions will bring on glaciation. We have still to consider the effect of the waters of the equatorial region on the one hand, and those of the higher latitudes on the other.

The average temperatures of the ocean waters at the surf line between 45° north and south latitudes, are as follows :[1]

For the belt between 15° north latitude, and 15° south latitude, 26 degrees centigrade.

For the belts between 15°–30° north latitude, and 15°–30° south latitude, 21 degrees centigrade.

For the belts between 30°–45° north latitude, and 30°–45° south latitude, 17 degrees centigrade.

The average temperature between 45° north latitude and 45° south latitude, at the depth of 1500 fathoms is between 2°–3° centigrade.

Professor Ditmar has found that at temperatures between 18°–21° C. that the dissociation tension of the bicarbonates of the sea water is five ten-thousandths of an atmosphere. On the other hand, at temperatures near zero, the dissociation does not take place, and the tension of course becomes nil. (See table above.)

The partial pressure of the CO_2 in the atmosphere at the present time is about three ten-thousandths. Therefore, he con-

[1]Compiled from tables Challenger's Rep., Vol. I, Table VI, at end of volume.

cludes that the warmer portions of the ocean are constantly supplying CO_2 to the atmosphere, and the colder portions are always removing it.[1]

The falling temperature which causes the glacial period must affect the temperature of the surface of the equatorial water, especially after an ice advance is inaugurated, but how much we cannot estimate. Taking the average surface temperature of these waters as 21°, and postulating the same fall of temperature as for the temperate waters, we see that the line $a'\ b'$ repsenting the decreasing dissociation due to the falling temperature, is much shorter than the line $c'\ d'$ or $c'\ e'$, representing the increase in the dissociation caused by the decreasing partial pressure of CO_2. However, the data upon which this part of the curve is based are much more conflicting and less satisfactory than those represented by the curve at 10°. But we may conclude that in the equatorial region the diminishing partial pressure has a greater effect than the postulated fall of temperature. But, with the increasing cold, the heated areas which can give off carbonic acid to the air are greatly diminished, especially after the glaciation has commenced, and this acts directly counter to the diminishing partial pressure.

In the northern seas whose surface temperature is near zero, each molecule of carbonate has the power to take up carbonic acid until it becomes a fully saturated bicarbonate. Just how much increase this area will undergo on an approach of a glacial period we cannot well estimate, but perhaps we can get a fair idea of it by comparing the area of the ocean contained within the circle of latitude which bounds the northernmost point of Greenland glaciation with that contained within the circle bounding the southern limit of Pleistocene glaciation. The ratio between these two areas is 2 : 5. These figures may not even approximately represent the real increase of the cold waters during glacial times, but they emphasize the fact of an actual and great increase in the amount of these waters.

The table on p. 609, as stated before, shows that at low tem-

[1] Chal. Rep., Vol. I, pp. 212, 213.

peratures the decrease in the partial pressure of the atmospheric CO_2 has practically no dissociating effect upon the bicarbonates of the ocean, and therefore that the large increase in the capacity for absorbing CO_2 is not affected by the diminishing partial pressure.

To sum up then: (1) the increase in the ocean's capacity for CO_2 at low temperatures, and (2) the invasions of the polar waters toward the equator, both tend directly to rob the atmosphere of CO_2, unaffected by any diminishing partial pressure of that gas. In the temperate waters the effects of increasing cold and decreasing partial pressure seem to be fairly evenly balanced, with a possible advantage for the diminishing partial pressure, against which must be reckoned a decrease in the amount of these waters. In the equatorial waters the effect of the decreasing partial pressure exceeds that of falling temperature, counterbalanced by a large decrease in the amount of these waters.

This division of the ocean with three belts shows us clearly the factors in the problem, but does not give us means by which to find the relative values of these factors—that is, to show us whether or not the intensifying factors, such as falling temperature and increasing areas of polar waters and decreasing areas of equatorial waters, more than counteract the effect of the diminishing partial pressure of the CO_2 over the temperate and equatorial waters.

In order to get some rough comparative value of these factors without pretending to get any accurate quantitative estimate of their actual value, we have tried to estimate the volume of the ocean water, whose temperature is reduced from 7° to 2°, from 12° to 7° and from temperatures above 12°, etc., and to calculate the amount of CO_2 these volumes of the waters can absorb on account of their lower temperature on the one hand and to estimate the greatest amount of CO_2 that might be freed from the tropical waters compatible with their restricted volumes on the other hand.

As shown in Fig. 6, we have assumed that the polar waters

(viz. those with temperature of 2°–3° C.) will advance southward at least as far as the southernmost limit of the ice-sheet. Therefore, we have started the line *a b* at 60° N. and S. latitude (the latitude of the southern Greenland glaciation) and the line *e h* at 37° (the latitude of the southernmost Pleistocene glaciation in North America). With this postulated southern advance of the cold waters, there must also have been a rise of these cold waters toward the surface. The amount of this rise is undeterminable at present. But since we have used Dr. Arrhenius' estimate of a drop of 5° in the temperature of the surface waters, we may assume the same fall of temperature for the body of the ocean. A given fall in temperature of the surface water must

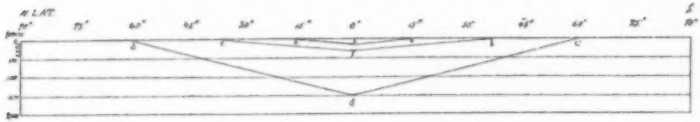


FIG. 6.—Section of ocean from north to south pole. Ocean taken at average depth of 2000 fathoms. Portion below 1500 fathoms has temperature below 2° to 3° C.

Line *a d c* incloses section of ocean whose temperature is now above 2° to 3°. Line *e f h* limits the equatorial and upward migration of the polar waters during maximum Pleistocene glaciation, when the ice reached the latitude 37° N.

Line *m k n* ditto for waters with Pleistocene temperature of 2° to 7°.

Above line *m k n* ditto for water of higher temperature.

take a very long time to communicate itself throughout the body of the ocean, but the larger the period during which the surface waters maintain their low temperature the more completely does the body of the ocean lose its extra heat.

At 1500 fathoms the temperature of the temperate and equatorial waters is 2°–3° C. above zero; therefore, the maximum depth which the line *a–c* reaches is placed at *d*. At 300 fathoms the warm waters have a temperature of about 7°.[1] Therefore, we place here *f* on the line *e f h*, designating the maximum advance upwards of the polar waters.

Point *k* on *m-k-n* is 150 fathoms below the surface and at that

[1] All temperatures calculated from tables of temperatures, given in Vol. I of the Challenger Reports.

depth the equatorial waters have average temperature of 12°. Therefore, this will be the limit of the waters of the belt that had temperatures of 2° to 7° during maximum glaciation. Above *K* are the waters which now have temperatures above 12°, and during glaciation temperatures above 7°.

To get a correct conception of this section of the ocean waters from pole to pole, we must multiply the length given here by 550.

The portion of the ocean below 1500 fathoms is already down to the limiting temperature; therefore, its carbon dioxide content is not subject to fluctuations. This leaves out of the 18 atmospheres of "free" CO_2 about 13 atmospheres above the 1500 fathom line.

The volume of these waters is divided as follows:

90° to 60° N. and S. latitudes, - - -	11%
60° to 37° " " - - -	24
37° to 6° " " - - -	65

Now, the volume of water included between *a d c* and *e f h* is considerably over one half that above the 1500-fathom line, or it holds about seven atmospheres CO_2, and a change of temperature from 7° to 2° represents a change in the dissociation of the bicarbonates from 1.9 to 2.00 (see Fig. 5, p. 610), or more than a 10 per cent. increase in the "free" CO_2. Therefore, this advance of the cold waters upward and toward the equator represents an increased capacity of the ocean for CO_2, equal to about seven tenths that of the present atmosphere.

The waters above *m k n* represent those which now have a temperature above 12° C. (we neglect the warm surface waters now spread far poleward by the warm currents), and it is in the warmer of these waters that the diminishing partial pressure of the CO_2 may cause a loss of CO_2 from the ocean.

Now this volume represented by *m k n* is considerably less than 2 per cent. of the volume above the 1500 fathoms line, so that for a limiting case if *all* the second equivalent were lost in these waters, instead of only at most a small portion of it, it would amount to less than one third that gained by the advance of the

cold waters, and in the actual case probably not more than one fortieth of the same.

Admitting all the inaccuracies of our assumption, still it seems to be clear that with falling temperature *the ocean will dissolve CO_2 from the air.*

The effect becomes more pronounced as the glaciers become more extensive and thus directly chill the ocean waters. We offer this as the most important accumulative factor causing the great extent of the glacial invasion, acting until overcome by a number of opposite agencies.

Dr. Chamberlin[1] has shown that the amount of CO_2 in the atmosphere at any one time, and therefore the climate of the earth at that time, depends upon the value of the ratio of the supply of the gas to its depletion. Besides the continuous supply that the atmosphere receives from the interior of the earth and from planetary space and the continuous depletion due to the formation of the carbonates in place of the igneous alkali earth silicates, there are variations in the ratio of supply to depletion dependent upon the attitude of the land and water.

A large exposure of land surface is correlated with a rapid solution of calcium and magnesium carbonates, and this solution is accompanied by a change from the normal carbonate to the bicarbonate form, and therefore represents a loss of CO_2 from the atmosphere.

On the other hand the formation of the normal carbonate by lime-secreting animals causes a direct liberation of the second equivalent of the bicarbonate. Therefore extensive oceans and abundant marine life are correlated with warm climate, and restricted seas and elevated land cause loss of CO_2 and colder climate.

Now, to investigate the rôle the ocean plays in this conflict:

1. The chief agencies in the *removal* of the carbon dioxide from the air are (a) the formation of the carbonates from the silicates; (b) the solution of the carbonates as bicarbonates. These are dependent upon the attitude of the land and water,

[1] See PROFESSOR T. C. CHAMBERLIN, JOUR. GEOL., Vol. V, p. 682.

the elevated land being accompanied by rapid disintegration and erosion. The increasing cold only slightly affects this process (a′) by the decrease in vegetation; (b′) by the slight decrease in chemical activity of the CO_2; (c′) by the freezing of the ground, preventing free percolation of the underground water, etc. But it aids disintegration by frost action, etc. (c) The polar seas constantly absorb CO_2 from the atmosphere. The increasing cold, with the increasing volume of cold waters, therefore *directly robs* the atmosphere of the CO_2. This process is not so marked in the warmer waters, because of the counteracting effect of the postulated diminishing partial pressure of CO_2.

2. The *supply of* CO_2, outside of that of plutonic and extraterrestrial origin comes (a) from the dissociation of bicarbonates in equatorial waters. The decreasing partial pressure aids this and the restricted area of warm water counteracts it. (b) The second equivalent of bicarbonate freed by lime-producing animals. The fall of temperature directly affects this most important source of supply, as it is well known that a fall of a few degrees in the ocean water would wipe out whole genera of test-producing animals.

To sum up, then: Accepting Dr. Chamberlin's proposition that the advance of a cold period is primarily dependent upon the altitude of land and water, the effect of the ocean is both to remove the atmospheric carbonic acid gas by the southern and upward invasion of the cold waters, and to decrease the supply of CO_2 to the atmosphere by the destruction of the lime-secreting animals. Therefore we conclude that *the ocean very greatly intensifies the secular variation of the earth's temperature, although acting as a moderating agent in the minor cycles.*

It is interesting to note what a different state of affairs we would have if the CO_2 in the ocean were simply dissolved as a gas from the atmosphere according to the laws of gas absorption. A diminution of the partial pressure of the CO_2 in the atmosphere, as postulated, would bring out of the ocean 38 to 45 per cent. of its great store of CO_2. A lowering of 5° in

temperature from 5° to 0° would only produce an increase in the solubility of the gas of 24 per cent., and from 20° to 15° of 14 per cent., and so, under such conditions, an excess of 14 to 31 per cent. of all the CO_2 in the ocean would have to be removed and consumed before a cold period could be inaugurated.

Although future investigations may cause a modification of Dr. Arrhenius' estimate, and such a change will affect some of these conclusions, the principles on which they are based will not be affected. If it be found that on account of certain intensifying agencies, or for other reasons, it is not necessary to postulate so large a decrease of the CO_2 of the atmosphere, or if this decrease is accompanied with a greater fall of temperature than 5°, then the depleting effect of the ocean will become more marked. If, however, the estimated decrease of the atmospheric CO_2 is too small, the intensive effects may be lessened, but probably not completely destroyed.

CYRUS F. TOLMAN, JR.

EDITORIAL

IT is gratifying to know that the excellent work of the Missouri Geological Survey is to be continued and that it is even proposed "to eliminate all ornamental or irrelevant fancies and go directly after the fundamental facts which make the only logical foundation for a geological survey." It is true that among the "ornamental" facts to be eliminated are such things as "Engineering Instruments, Photographic Apparatus, Laboratory Equipments" and a few others which ordinary geologists have come to consider indispensable. However, it is no ordinary man or ordinary plan of work that Missouri now has on its hands. In a recent St. Louis interview the state geologist announces that "The rocks have never been differentiated in Missouri and Arkansas"—thus setting aside at one stroke of the pen all the results of former work in the region. Fortunately such a dire condition is not to be allowed to continue, and the new state geologist proposes to issue at once a preliminary report in which "I will differentiate the rocks to a finish." He also proposes to give "photographic views of two or three of the best exposures of each rock in the state," from which we may infer that since his *Biennial Report* was issued he has fallen into evil ways and has begun to lean a little on the "ornamental" and "irrelevant" aids of other members of his profession. This new work is to be very thorough and the sedimentary rocks are to be taken, "one at a time, from Z to A."

Incidentally he will courteously give in the report a synopsis of a new "cosmic philosophy" which he has worked out "with only physics, logic and consciousness as guides." With such noble companionship it is no wonder that ordinary grammar is considered out of place. At least we may judge this to be true from such statements as, "Several dykes of diabase were crossed

in the county, as well as rumors of rich deposits, etc."[1] This sentence gives one some new light on classification and will perhaps obtain for the doubter pardon for his skepticism whether the new differentiation is to be so very thorough after all. When diabase dikes and rumors are classed together, there seems room for doubt as to the closeness of the classification. However, all things are possible to one who can explain dolomite as formed in Sargasso seas and can settle the glacial problem in one short page. The proposed preliminary report will be eagerly awaited; the *Biennial* is all too brief a pleasure.

H. F. B.

[1] Biennial Report of State Geologist, 1898, p. 36.

Reviews.

The great Ice-dams of Lakes Maumee, Whittlesey and Warren. By Frank Bursley Taylor, Fort Wayne, Ind. American Geologist, July 1899, Vol. XXIV, pp. 6–38, Pl. II and III.

Two years ago Mr. Taylor contributed to Pleistocene geology a new working hypothesis.[1] Pointing out that the recessional moraines left by certain lobes of the Laurentide ice sheet on plains or in broad smooth valleys were characterized by regularity of interval, he postulated that this regularity was caused by a definitive rhythm in the general conditions controlling the magnitude of the ice-field; whatever may have been the cause of the general wasting of the ice, its action was modified by a concurrent cause of a rhythmic nature, which alternately promoted and opposed the wasting. Under the joint action of the two causes the ice front first retreated with comparative rapidity, then halted, readvanced slowly over part of the abandoned territory, and finally halted a second time before beginning a second cycle; and each recessional moraine marks the position of the ice front at the close of such a cycle. This hypothesis, if well founded, is of far reaching importance. It affords a basis for the correlation of moraines in widely separated districts, and for the mapping of the ice sheet at various stages of its final waning. It affords a regularly graduated chronologic scheme of classification. It leads to an estimate of the duration of a definite portion of geologic time, far superior to any based on phenomena of erosion. And it probably assists in the discussion of the cause of the ice age.

When the hypothesis was first presented it was applied to the making of a time estimate. In the present paper it is applied to local geology, the correlation of moraines and associated phenomena in a district about Lakes Erie and Huron. After a general discussion of the function of the ice front as a dam to retain glacial lakes, and of the theoretic relations of successive positions of the dam to cols, and the

[1] Moraines of Recession and their Significance in Glacial Theory. Jour. Geol. Vol. V, 1897, pp. 421–465.

resulting location of shore lines and channels of outlet, an account is given of the actual positions of the ice-dam within the district and of the resulting series of glacial lakes. A map of moraines includes not only data from various sources previously publisht, but important new material, especially for the Canadian peninsula, and is adjusted to the subject in hand by the indication of the theoretic continuations and connections of partly surveyed moraines. Other maps show the glacial lakes, outlined with detail and confidence not only on the land side, where their shores are still preserved as dry beaches and terraces, but also the ice side, where all actual vestige has necessarily disappeared.

Lake Maumee, in the western part of the Erie basin, lasted during three oscillations of the ice front, growing larger with each shifting of the dam. At first its discharge was at Fort Wayne and thence down the Wabash River; afterwards part of its surplus escaped across the "thumb" of Michigan at Imlay, running westward to the Lake Michigan basin. In the later part of its life the broad upland of the peninsula of Canada was a nunatak. Lake Whittlesey, succeeding Lake Maumee in the same basin, held place for a single morainic cycle. The Canadian upland, no longer a nunatak, formed part of its northeastern shore, separating two ice lobes. Its discharge crost the thumb of Michigan at Ubly to a lower glacial lake, Saginaw, and thence ran westward through the Pewaino channel across the lower peninsula of Michigan. Lake Warren, uniting Lakes Whittlesey and Saginaw, at the level of the latter, endured for four morainic cycles, being greatly modified in outline by the successive changes of the retaining dam and becoming eventually much larger than its predecessors.

It is to be noted that the author did not delay the publication of his generalization until the ground had been wholly covered by observation nor until all the observations made use of had been verified. While guarding against misapprehension by constantly drawing the line between fact and theory, he has freely used his working hypothesis for purposes of local interpolation. To whatever extent his local generalizations are deductions from theory they will eventually, through the extension of observation be made to serve as tests of the theory.

Taylor dwells on the peculiar significance of the Ubly channel as an evidence of the existence of glacial lakes and a glacial dam, and closes with a general argument (drawn out by criticisms of J. W. Spencer) in support of the fundamental theory that the ice sheet served as a dam for the retention of lakes.

A corollary of some interest, not mentioned by the author, relates the history recorded by recessional moraines to that associated with Niagara gorge. From the beginning of the last ice retreat at Cincinnati Taylor counts seventeen moraines to Rochester, beyond which point new conditions enter, making the continuance of the analysis a matter of great difficulty. But just at the close of the term represented by these moraines the Niagara began its work, so that the moraine history is complemented by the river history. Together they represent all the time since the latest ice maximum, a period whose measurement in years is far more valuable to science than the determination of the age of the great cataract. Postulating the astronomic cycle of the precession of the equinoxes as the cause of the morainic cycle, the approximate time covered by the morainic history is computed (by the reviewer) at 315,000 years. This is so long a period in comparison with the most ample of modern estimates for the age of the Niagara that the uncertainty as to Niagara's age is of little moment in considering the sum of the two periods. Broadly stated, the hypothesis that the recessional moraines are functions of the precessional cycle estimates the time since the last maximum of glaciation at 300,000 to 400,000 years.

G. K. G.

The Influence of the Carbonic Acid in the Air upon the Temperature of the Ground. By PROFESSOR SVANTE ARRHENIUS. *Philosophical Magazine and Journal of Science*, Vol. XLI (Fifth Series) 1896, pp. 237–276. *La Revue Générale des Sciences*, Mai, 1899, pp. 1–22.

Professor Arrhenius was led to investigate this subject by the debates among the Swedish geologists upon the cause of the glacial and interglacial climates of the Pleistocene. The conclusion that none of the current hypotheses are satisfactory or at all competent to explain the observed phenomena led him to calculate the quantitative effect of any given variation in the amount of atmospheric carbon dioxide upon the temperature of the earth's surface. The fact that the carbon dioxide and water vapor are the chief agents in retaining the heat radiated from the earth's surface had long been known qualitatively and even the relative values of the selective absorption of radiant energy for the various atmospheric gases had been determined, but it remained for

Professor Arrhenius to show the exact effect of any given change in the carbon dioxide content of the atmosphere upon the surface temperature of the earth.

The essential work of the physicist and mathematician having now been done by him, it remains for the geologist to investigate the various sources of supply and depletion of carbon dioxide and to determine if possible if there have been any variations of such an order of magnitude as to produce the results observed.

Professor Arrhenius explains in his papers that the air retains heat (light and dark) in two different ways: (1) The heat suffers a selective diffusion as it passes through the air. This is greatest for the rays having short wave-lengths (ultra-violet) and insensible for those of long wave-lengths which form the chief part of the radiation of a body of the temperature of the earth, viz., 15° C. (2) The gases themselves have the power of absorbing selectively the light and heat of certain wave-lengths. The carbon dioxide and the water vapor have this power of selective absorption to a far greater extent than the oxygen, nitrogen or argon, and this absorption is not distributed evenly throughout the spectrum but occurs in certain definite bands which are best developed in the ultra-red portion which represents the rays with long wave-lengths such as are given off by bodies with a low temperature.

There are two ways in which to measure the amount of the heat absorption by the carbon dioxide and the water vapor: (1) by measuring directly the amount of heat absorbed by such quantities of these gases as they appear in the atmosphere, and at a temperature of 15° C., and (2) by measuring the amounts of heat received from the full moon at different heights above the horizon. The amount of carbon dioxide through which the rays pass is evidently a function of altitude of the moon above the horizon, while that of the water vapor depends both upon the altitude and the humidity of the air.

Professor Arrhenius takes the second method and from Professor Langley's observations on the heat received from the full moon at various altitudes above the horizon he calculates the amount of heat absorbed by the two gases by an atmosphere having the present average amount of carbon dioxide and the average amount of water vapor, viz., ten grains per cubic meter at the earth's surface. The full moon has, however, a surface temperature of 100°, and he introduces the corrections necessary to apply the above to a body with the temperature of 15° C.

With these data it is not difficult to calculate the effect of any change in the amount of carbon dioxide upon the temperature of the surface of the earth. The temperature of the earth's surface is theoretically in equilibrium with that of the atmosphere. Now if by any increase in the amount of the carbon dioxide the atmosphere retains more heat than before, it will radiate more heat to the surface of the earth. The surface temperature then will rise until there is again an equilibrium between the two. This rise is governed by Stefan's law which states that the intensity of the radiation is proportionate to the fourth power of the er

From these data Professor Arrhenius finds that if the carbon dioxide is increased 2.5 to 3 times its present value, the temperature in the arctic regions must rise 8° to 9° C. and produce a climate as mild as that of the Eocene period. A diminution to 0.62 to 0.55 of its present value must cause a fall of from 4° to 5° C. and give us a glacial period.

It is to be noted that in every case throughout the calculation Professor Arrhenius has preferred to slightly underestimate the effect of the carbon dioxide than to risk a possible overestimate. Also where he has been compelled to use interpolation the limit of error has been well within the degree of accuracy of the observations upon which they are founded.

The tremendous interest of these considerations, not only as a basis for the interpretation of the past history of the globe but also for the prophecy of its future, demands an investigation of the problem along the lines of direct experiment, as a supplement to the elegant calculations of Professor Arrhenius. CYRUS F. TOLMAN, JR.

Special Report on Gypsum and Gypsum Cement Plasters. By G. P. GRIMSLEY and E. H. S. BAILEY. University Geological Survey of Kansas, Vol. V. Pp. 183, 30 plates. Topeka, 1899.

Among the minor mineral industries of the country those connected with gypsum have been, so far as literature is concerned, heretofore neglected. The present report is accordingly particularly welcome. The papers so far accessible have been, in the main, devoted to the description of local deposits and the technology of the gypsum industries has not been described before in any adequate manner. The present volume includes not only a description of the Kansas gypsum beds

but brief notes on the gypsum of other states and countries and a full discussion of the mining and milling processes. The body of the work is by Dr. Grimsley while Professor Bailey contributes a welcome chapter dealing with the chemistry of the subject.

In 1897 Kansas produced 50,045 tons of gypsum which had a value of $252,811. It was a little behind Iowa in production and ahead in values; the difference being in the large proportion of the Iowa product sold as land plaster. Aside from these two states Michigan and New York are the main producers. The Kansas gypsum is found in three fields; the Northern or Blue Rapids area mainly in Washington and Marshall counties, the central or Gypsum City area of Salina, Dickinson, and Marion counties, and the southern or Medicine Lodge area in Comanche and Barber (misprinted Barton on map) counties. The beds occur in the Permian of Prosser's classification and the deposits include the original rock deposits and the derived gypsum earths which are of recent origin. These gypsum earths are the distinctive beds of the Kansas-Oklahoma district and are thought to be marsh deposits deriving their peculiarities from the secondary deposition of gypsum in clays. They are used in the production of gypsum cements and are mined by ordinary surface methods. The rock gypsum is won by underground mining on a room and pillar system, of which a more detailed account would have been valuable, and are used in the production of plaster of Paris and other products.

The Kansas milling practice does not seem to differ from that of other districts especially, though the Stedman disintegrator has been introduced and a cooling air blast is used at one point to elevate the calcined plaster. Here as elsewhere grinding is in the main done by stones and it seems peculiar, in view of the great progress of recent years in fine grinding machinery, that the numerous experiments in the direction of cheaper and more expeditious grinding have never borne fruit in the gypsum industries. Burning is done in the ordinary Marsh calcining kettle. It would seem that in the case of the gypsum earths at least the rotary furnaces now so much used could be applied to advantage.

In the discussion of the set of the plaster Dr. Grimsley has contributed some highly interesting and valuable microscopic studies in which he shows, in brief, that the strength of the set plaster depends upon the formation of a network or felt of fine lath-shaped crystals and that the quickening agents in this setting process are the few small

crystals present in the dry plaster. This accords well with all the known facts in the case and is furthermore in line with Jameson's observations on the setting of Portland cements. It explains some of the peculiarities of the behavior of retarders though in the matter of that vexed subject but little that is new is brought out. If the subject of the strength, and rapidity of set of the gypsum cements could have been gone into a little and illustrated by tensile strength and other tests it would have added greatly to the value of the book and have aided in defining the sort of situations in which these cements could be used to best advantage. In the form of hard white finish they now dominate the market so far as interior work is concerned but the advisability of using them for wall work in any general way is open as yet to some question. This is particularly true in view of the strength and cheapness of magnesian limes and the availability of non-sulphate cements.

Dr. Grimsley's report is a valuable one, particularly in its technical as distinguished from its geological phases. It will undoubtedly have a large influence on the gypsum industry of the state and is a credit to the vigorous Kansas Survey. H. F. BAIN.

American Cements. By URIAH CUMMINGS. Pp. 299, 8 vo. Rogers & Manson, Boston. 1898.

In the rapid introduction of Portland cements in this country the importance and value of the Roman cements bid fair to be overlooked. At present there is what the author fittingly nominates a "craze" for quick setting, high testing cements, and the slower setting, cheaper grades are looked upon in many quarters as of very little value. Mr. Cummings' long experience in the manufacture of cement and his wide interest in the subject admirably fit him to discuss it. In this little book he has gathered together much scattered information and has added very much from his own experience. His interpretations of the chemical processes involved in the making and the setting of cements will, doubtless arouse much opposition; particularly in his plea for the magnesian cements, but where so much is uncertain any hypothesis backed with such facts as Mr. Cummings marshals must necessarily receive careful attention. Taken as a whole the book is one of which no one interested in cements and the utilization of our limestones and shales, can afford to remain in ignorance.

H. F. BAIN.

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